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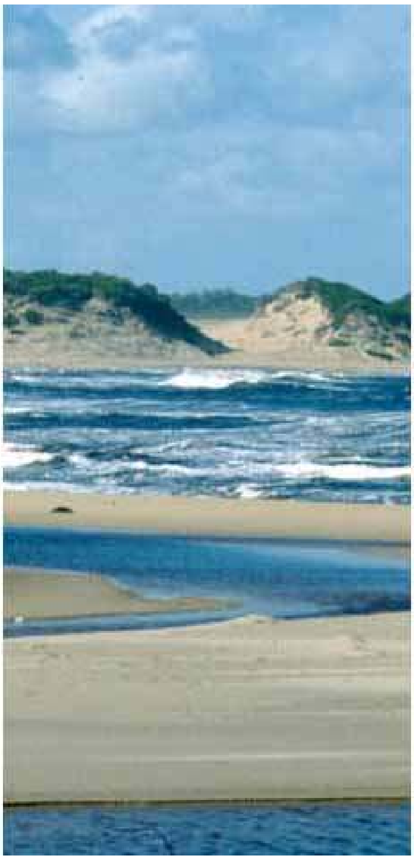
Indicative Mapping of Tasmanian Coastal Vulnerability to Climate Change and Sea-Level Rise: Explanatory Report

2nd Edition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Front cover photos: Sandy coasts are mobile landforms which are highly vulnerable to erosion and increased dune mobility in response to sea-level rise. The centre image depicts a beach and dunes at Nye Bay (southwest Tasmania) whose current active erosional state is probably primarily a response to renewed global sea-level rise during the 20th Century. However, sandy shores are not the only coastal landform type potentially vulnerable to accelerated erosion with sea-level rise. The left-hand image shows a shoreline of clayey-gravelly semi-lithified Tertiary-age sediments at Cornelian Bay (Hobart) which has receded several metres over the last few decades in response to wave erosion. Coastal cliffs (right-hand image) are another landform type which typically show ongoing erosion even with stable sea levels, and may show accelerated rock-falls and slumping in response to sea-level rise. This will be particularly evident where coastal cliffs are composed of only semi-lithified bedrock, as is the case for the Tasmanian cliff depicted here.

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FOREWORD TO 2ND EDITION

The first edition (Sharples 2004a) of this report and its accompanying mapping provided indicative ("first pass") mapping of Tasmanian shorelines vulnerable to two coastal hazards related to projected sea-level rise, namely storm surge flooding and the erosion of sandy shorelines. In addition, the distribution of a type of shoreline considered to have minimal vulnerability to coastal hazards related to sea-level rise was also mapped (moderately sloping hard-rock coasts). However Tasmanian coasts vary widely in their geological and geomorphic (landform) characteristics, and whilst the indicative flooding mapping was comprehensive for the entire Tasmanian coast, in terms of erosion hazards the identification of sandy shores vulnerable to erosion, and of robust minimal vulnerability shores, accounted for only 45% of the length of the Tasmanian coast. The other 55% remained to be classified as being either robust shores having minimal vulnerability, or non-sandy coasts having erosion, slumping, cliff instability or other vulnerabilities.

This second edition of the indicative coastal vulnerability mapping was undertaken to identify non-sandy shores potentially vulnerable to a range of other coastal geomorphic hazards that may result from sea-level rise. Following recommendations made in the first edition of this report, non-sandy shoreline types potentially vulnerable to the following hazards were identified:

- Soft muddy shores potentially vulnerable to change;
- Soft (clayey-gravelly) or colluvial (slope deposit) shores potentially vulnerable to progressive erosional retreat and / or slumping; and
- Hard-rock sea cliffs potentially vulnerable to rock falls, collapse, slumping and cliff-line retreat.

In part, the identification of these additional coastal hazard types was made possible by the addition of further mapping data to the coastal geomorphic map of Tasmania upon which much of this indicative vulnerability assessment has been based, including further field mapping and the incorporation of new geological and geomorphic information provided by Mineral Resources Tasmania.

As a result of this additional indicative vulnerability mapping, a total of 84% of the Tasmanian coastline length has now been indicatively mapped as either being potentially vulnerable to a range of coastal geomorphic hazards related to sea-level rise, or as having minimal vulnerability to these hazards. The remaining 16% of the coast that remains unclassified mostly comprises less common shoreline geomorphic types – some of which will be vulnerable and some less vulnerable – but which will probably mostly need to have their vulnerability assessed on a site-specific basis.

In undertaking this work, the following additions, changes and upgrades have been made to the First Edition of this work (Sharples 2004a) to produce this Second Edition:

- The coastal geomorphic line map (*tascoastgeo_v3*) upon which the vulnerability mapping *tascsthz* produced by Sharples (2004a) was based, has been upgraded in a number of ways. These upgrades include the addition to the map of several east coast tidal lagoons that were not previously included in the map (e.g., Henderson Lagoon), and the incorporation of new field mapping data based on additional fieldwork by C. Sharples since 2004. Further geomorphic and geological data from other sources has also been incorporated, including new geological and slump hazard mapping by Mineral Resources Tasmania (Mazengarb 2004a,b, 2005, 2006; C. Calver *pers. comm.*). These changes resulted in more confident classification of some shorelines that were difficult to interpret from air photos (on which much of the original line map was based), but have mostly not affected sandy shores since these were previously mapped from air photos at a high level of confidence in all except the case of some very narrow sandy shores. Nonetheless, the most significant mapping change of this sort has been the re-classification of some shores in the Robbins Island region of far northwest Tasmania, which were previously classified as "muddy-silty" shores on the basis of an interpretation of earlier mapping by Munro (1978), but which have now been re-classified as "sandy shores" since this better reflects their actual sedimentological texture (fine sands).

The attribute table of the coastal geomorphic line map has also been edited and re-organised in several ways, including the re-naming of a number of attributes, re-numbering of several attribute codes to make the attribute code system more logical and systematic, and deletion of several attributes now considered redundant (and not used in the vulnerability mapping). These changes have resulted in the production of a new version of the coastal geomorphic line map, *tascoastgeo_v4gda*, upon which the vulnerability mapping provided with this report (*tascsthz_v2*) is based. The changes to the line map are fully documented in the Data Dictionary for *tascoastgeo_v4gda* (Sharples 2006), and are reflected in the Data Dictionary for *tascsthz_v2* which forms Appendix 2 of this report.

- Using the upgraded *tascoastgeo_v4gda* geomorphic map, the indicative mapping of sandy coast erosion vulnerability (*sandy* attribute) and minimal vulnerability shorelines *(minhaz* attribute) that was provided in the first edition of this vulnerability mapping (*tascsthz*) has been redone using the same method as applied to the first edition (Sharples 2004a), but taking account of the new attribute names and attribute codes where relevant. The result is the *Sandyvuln* and *Minvuln* attributes of the 2nd Edition coastal vulnerability map *tascsthz_v2*. The resulting vulnerability mapping involves very little change to the indicative mapping of these coastal vulnerability categories from the first edition, with only a few differences resulting from ground truthing in certain areas since 2004 (the most significant change being the inclusion of sandy shores in the Robbins Island region, that were previously classified as "muddy silty" shores).

- Using the upgraded *tascoastgeo_v4gda* geomorphic map, indicative mapping of several new coastal vulnerability types has been undertaken, namely semi-lithified (soft) clayey-gravelly or colluvial (slope deposit) shores potentially vulnerable to progressive erosional retreat and / or slumping (*Erosvuln* attribute), hard-rock sea cliffs potentially vulnerable to rock falls, collapse, slumping and cliff-line retreat (*Cliffvuln* attribute), and soft muddy (mainly estuarine and deltaic) shores potentially vulnerable to change (*Muddyvuln* attribute).

- Significant changes to this 2nd Edition report include changes to the Data Dictionary (Appendix 2) documenting updates to the coastal line map described above, sections and text added to this report to describe the mapping of the above new vulnerability categories (in Sections 2.0 & 4.3), and incorporation of revised statistics indicating the proportions of the Tasmanian coast now covered by indicative vulnerability mapping (see Summary and Section 4.3). Due to the addition of several tidal lagoons to the coastal line map, the total length of the Tasmanian coastline cited in this report is now some 34 km longer than the length cited in the first edition of this work (Sharples 2004a). A new set of maps illustrating parts of the vulnerability mapping have been provided in Appendix 1, including a map identifying coastal segments comprising the 16% of the coast whose vulnerability remains unclassified (Figure 50). In other respects the text of this report remains essentially unchanged from the first edition, although a variety of minor editing corrections and additional information have been incorporated in various places throughout the text. These do not change the key outcomes or implications of this report in any significant way from those documented in the first edition (Sharples 2004a).

The flooding vulnerability mapping element of this work (Sections 2.2 & 4.3.2) remains unchanged from the first edition.

SUMMARY

Considerable geological and geomorphic evidence, direct observations of subsiding coasts, theoretical considerations and experimental investigations demonstrate that rising sea levels result in significant physical changes to shorelines, as they adapt to the changing sea-level conditions. Physical changes resulting from sea-level rise, especially on soft sandy shores and in low-lying coastal areas, are likely to be sufficiently significant in some areas, over future decades, as to pose risks for buildings, roads and other infrastructure in vulnerable coastal locations, as well as causing changes to coastal landform process systems and biological communities.

This report describes and explains a digital map set that was developed during 2004 - 2006 to provide an indicative (or "first pass") identification of Tasmanian coastal areas potentially vulnerable to increased storm surge flooding, shoreline erosion, rock falls, and slumping as a result of global climate change and sea-level rise. The mapping additionally identifies some Tasmanian shores having minimal vulnerability to these hazards.

In this report, the term *risk* refers to the combination of *hazard* and *vulnerability*, where the *hazard* is a physical process or event – such as sea-level rise or storm surge events – and *vulnerability* is the degree of exposure of things, such as coastal landform features, to the impacts of the hazards[1]. In these terms, the assessment presented in this report and the accompanying mapping is essentially an assessment of Tasmanian coastal landform *vulnerability* to the *hazards* of climate change and sea-level rise. The use of this vulnerability assessment to assess the *risks* to valued socio-economic or ecological assets (for example, economically valued infrastructure, significant saltmarsh communities or prized beach environments) is a further stage of risk assessment which has not been undertaken here, but for which this indicative vulnerability assessment provides a basis.

Coastal landforms, particularly "soft" shores such as sandy coasts, are one of the most mobile and dynamically changing geomorphic (landform) environments on Earth. Even in the absence of sea-level rise and climate change, coasts can and do change their physical form significantly over relatively short periods. Flooding and shoreline erosion have affected Tasmanian coasts repeatedly over the last 6,500 years – while sea level has been mostly steady – and in many cases these ongoing changes pose risks for inappropriately-sited coastal development in Tasmania. It is important to be aware that sea-level rise and climate change are not the only causes of coastal hazards in Tasmania, however the renewed sea-level rise and climate change that has commenced over the last century or so is likely to increase or accelerate coastal flooding and erosion hazards where these have existed previously, and to initiate new phases of erosion on some shores that were previously in equilibrium.

Following about 6,500 years of relative sea-level stability, a renewed global sea-level rise of 10 – 20 cm has occurred during the last century. A sea-level rise relative to the land of about 14 centimetres since 1841 has been measured on the south-east Tasmanian coast, much of it probably having occurred during the last century. Global mean sea-level rise accelerated during the 20th Century, and an ongoing global sea-level rise of between 9 and 88 centimetres is now projected to occur by 2100 relative to 1990 sea level. In addition, it is possible that coastal storms of a given magnitude may occur more frequently over future decades than in the past.

The physical (geomorphic) effects of ongoing sea-level rise and climate change on Tasmanian coasts over future decades are likely to include (but are not limited to):

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1 Some workers use the term "sensitivity" in the way "vulnerability" is used here, and use "vulnerability" in a different sense (see Section 1.6), however the usage adopted in this report is more traditional in geohazards work.

- increased flooding of low-lying coastal areas during storm surges;
- erosion and landwards recession of soft sandy shorelines, particularly where these are backed by low-lying plains of soft unconsolidated sediments;
- increased mobility of coastal sand dunes, triggered by sandy shore erosion and potentially by climate stress on dune vegetation cover;
- modification of soft low-lying muddy estuarine and deltaic shores;
- acceleration of existing progressive erosion of soft clayey-gravelly shorelines (e.g., Tertiary-age sediment shores);
- increased slumping of steep landslip-prone shorelines, including shores of basalt colluvium, Tertiary-age sediment, and intensely fractured and weathered bedrock shores;
- accelerated rock fall, cliff-collapse and retreat of vertical or near-vertical bedrock sea cliffs; and
- rising coastal groundwater tables and increased penetration of salt water wedges into coastal ground waters.

On the other hand, some gently to moderately sloping hard bedrock shorelines are likely to show little physical change or significantly increased flooding in response to sea level rise over the next century.

Certain basic geomorphic (landform) characteristics – which are referred to in this report as *fundamental vulnerability factors* – predispose certain types of shores to being potentially susceptible to one or more of the physical coastal changes (above) expected to occur as a result of sea-level rise. Such changes are "risks" insofar as they are likely to threaten the integrity of infrastructure and assets that have been placed on vulnerable coasts without due consideration of sea-level rise.

However, the degree to which any particular shore having the fundamental vulnerability factors predisposing them to a certain coastal hazard will actually be changed (or "impacted") by that hazard may vary considerably depending on a wide range of local climatic, oceanographic, geological, geomorphic and topographic factors or variables which are here referred to as *regionally and locally variable vulnerability factors*. Complex feedback processes between the various processes and variables affecting particular shores mean that whilst some shores may respond to sea-level rise in relatively simple ways – e.g., by simple erosion and recession as described by the well-known "Bruun Rule" of erosion by sea-level rise – on some other shores the effect of sea-level rise can be overwhelmed by other local conditions which cause the shore to behave in different ways that the Bruun Rule would not predict.

For example, the *fundamental vulnerability factor* predisposing an open (oceanic) coast sandy shore to significant coastal erosion and recession in response to sea-level rise is the exposure of sandy shores backed by low-lying sandy sediment deposits to storm wave attack. However, there are situations in which the effects of littoral (longshore) sand drift and sediment budget may be such as to cause such sandy shorelines to respond to sea-level rise by prograding (growing seawards) rather than receding. This is likely to be the case at the southern end of Ocean Beach (western Tasmania), where sand eroded from the northern parts of the beach (see Figure 6) is drifting southwards and accumulating at the southern end, which is consequently prograding and is likely to do so more rapidly in future as sea-level rise causes accelerated erosion and southwards drift of sand from the northern parts of the beach.

Assessments of coastal hazards resulting from (or increased by) climate change and sea-level rise can occur at several different levels of detail and reliability (see detailed discussion in Section 3.0):

- *Indicative (or "First Pass") Assessments* involve simply the identification of coasts having the *fundamental vulnerability factors* predisposing them to particular coastal hazards. This approach has the advantage of rapidly providing planners and managers with a precautionary basis for making decisions on coastal development in areas where more detailed coastal vulnerability assessments are lacking, however it does not specify the *degree, pattern or rate* at which particular shores are likely to be impacted by coastal hazards.

- *Regional (or "Second Pass") Indicative Assessments* are indicative assessments in which a number of key *regionally variable vulnerability factors* are taken into account in addition to the *fundamental vulnerability factors*. This level of assessment can begin to rank different coastal areas in terms of the likely relative degree to which they may be impacted by a coastal hazard.

- *Site Specific Assessment and Modelling*, incorporating all *locally and regionally variable vulnerability factors*, is the most reliable means of predicting the likely degree, pattern and rates at which coastal hazards may impact on a particular coastal stretch or area that has been identified as potentially vulnerable by an indicative first pass assessment. However this level of assessment requires a considerable investment of time and money.

- *Shoreline Monitoring and Refinement of Models* involves regular repeated quantitative physical measurement of the form, profile and geomorphic processes of particular shorelines over periods of time long enough to reliably discern long-term trends and patterns of shoreline change. Such data can be used to test and refine site-specific coastal behaviour models (above), and so monitoring should be an integral component of any site-specific modelling. This approach to coastal vulnerability assessment is by definition very time consuming, however it is the only approach that can yield definitive data on actual trends in shoreline change.

The digital mapping accompanying this report provides an Indicative ("First Pass") Assessment of the entire Tasmanian coast (including the Bass Strait islands and other major islands, but excluding Macquarie Island) that identifies coastal areas potentially vulnerable to:

- storm surge flooding
- erosion and landwards recession of sandy shorelines
- changes in muddy estuarine and deltaic shores
- progressive erosional retreat and / or slumping of soft (typically clayey-gravelly) bedrock or colluvial shores
- rock falls, collapse, slumping and retreat of hard-rock coastal cliffs

The digital mapping additionally provides an indicative identification of:

- moderately sloping hard-rock shores with minimal potential vulnerability to hazards resulting from climate change and sea-level rise

Indicative Storm Surge Flooding Vulnerability
Coastal areas potentially susceptible to storm surge flooding have been identified on the basis that the *fundamental vulnerability factor* for this hazard is the presence of significant areas of low-lying low-profile land immediately landwards of the mean high water mark. For the purposes of this assessment, vulnerable low-lying coastal areas are considered to be those lying within the height range of historically recorded 0.01% exceedance (roughly 2 – year return period) storm surge event water levels, or likely to do so as a result of projected future sea-level rise. Storm surge water levels were obtained from the seven Tasmanian tide gauge stations with sufficiently long records, and have been interpolated in a linear fashion between these tide gauges around the Tasmanian coast. Low-lying coastal areas within the height range of flooding by 0.01% exceedance storm surge events were identified for the entire Tasmanian coast using the best digital topographic dataset available at a state-

wide coverage, namely the 25m Digital Elevation Model (DEM) of Tasmania. Potential flood areas were mapped for three scenarios, namely:

- 0.01% exceedance flood levels above mean sea level for 2004;
- 0.01% exceedance flood levels above the minimum projected sea level for 2100; and
- 0.01% exceedance flood levels above the maximum projected sea level for 2100.

The potential flood vulnerability areas obtained by using the 25m DEM in this way are of variable accuracy or spatial resolution around the Tasmanian coast, depending on the differing topographic data sources used to construct the 25m DEM in different parts of the state. Fortunately, in many of the more urbanised coastal areas – where coastal hazard risks to infrastructure are a bigger problem – the DEM has been constructed from relatively high-resolution 1:5,000 ortho-map contours. In all cases, however, the indicative coastal flood vulnerability zones identified by the maps accompanying this report should be considered purely as areas *potentially* prone to storm surge flooding, which are thus identified as areas that should be subjected to more detailed site-specific assessments of flood vulnerability.

The total areas of the Tasmanian coastal zone above the mean high water mark (including Bass Strait islands and other major islands apart from Macquarie Island) that have a potential storm surge flooding vulnerability under each of the 3 scenarios assessed are as follows (determined from the digital polygon maps created for each scenario from the 25m DEM):

Scenario	**Indicative coastal area vulnerable to storm surge flooding in a 0.01% exceedance event (km^2)**	**Digital map file (shapefile)**
2004 0.01% exceedance storm surge flood levels	240	*fldhz2004_gda*
Minimum 2100 0.01% exceedance storm surge flood levels	247	*fldhz2100min_gda*
Maximum 2100 0.01% exceedance storm surge flood levels	328	*fldhz2100max_gda*

It is notable that in many coastal places the areas of land that may potentially be flooded under higher projected future sea levels are only a little greater than under present sea levels, due to certain characteristics of the topography of many low coasts in Tasmania (see Section 4.3.2). However it is important to note that significantly greater flood-water depths and potentially increased frequencies of storm surges will cause additional flooding impacts beyond simple increases in the (horizontal) areas of coastal land prone to flooding.

Other Indicative Coastal Vulnerabilities, and Minimal Vulnerability Shores

Coastal areas with a potential sandy shore erosional recession vulnerability have been indicatively identified on the basis that the *fundamental vulnerability factors* for this hazard are the presence of unconsolidated sandy shores backed by low-lying plains of unconsolidated (usually sandy) sediment. These shores have been sub-divided into open-ocean shores and coastal re-entrant shores, on the basis that erosion and recession of these two types in response to sea-level rise are partly governed by significantly differing geomorphic processes. Sandy shores immediately backed by hard bedrock rather than sandy sediment plains have also been separately identified, since whilst these may be subject to beach erosion – and potentially to complete loss of beaches – their potential for significant landwards shoreline recession in the short to medium term is limited.

Soft muddy shores have been separately identified as being vulnerable to change (including erosion) with rising sea levels and climate change, on the basis that their sedimentological characteristics mean they may behave differently to sandy shores, and also because many of them are composed of estuarine or deltaic sediment deposits whose response to climate change may be partly determined by fluvial processes in their inland river catchments.

A further category of "soft" shoreline has also been indicatively mapped as a separate vulnerability category. These are typically clayey-gravelly textured shores of semi-lithified or deeply weathered bedrock, and shores composed of unconsolidated slope deposits (including old landslide debris). Again, these are likely to behave differently to either sandy or muddy shores, and their response to sea-level rise may vary from simple progressive erosion on low profile coasts, to erosion accompanied by slumping (landslides) on steeper coastal profiles.

Finally, hard-rock sea-cliffs have been identified as a further coastal vulnerability category since these may be prone to rock-falls, slumping and collapse both under present-day conditions, and more so in response to projected future sea-level rise. The distinctive characteristics of these shorelines again means that they will probably behave differently to any of the other above categories.

An important category of indicative minimal vulnerability shores has also been identified, on the basis that the *fundamental minimal vulnerability factors* for this type of shoreline are gently to moderately sloping hard bedrock shores without significant unconsolidated slope deposits or talus deposits, and without vertical cliffs rising greater than 5 metres vertically from the high water mark. These shores are indicated to have minimal vulnerability either to flooding or to the various types of erosional impacts noted above.

The above shoreline types were identified for all Tasmanian shores using the 1:25,000 digital shoreline geomorphic types line map of Tasmania (*tascoastgeo_v4gda,* and the derived map *tascsthz_v2gda*), which contains comprehensive data on the relevant fundamental vulnerability factors for all Tasmanian shorelines. The shores indicated to be potentially vulnerable to the hazards described above, and indicative minimal vulnerability shores, are mapped in the digital line map *tascsthz_v2gda* accompanying this report using the attributes *Sandyvuln, Muddyvuln, Erosvuln, Cliffvuln*, and *Minvuln*. Shores not yet classified as either being vulnerable to any of these hazards, or as having minimal vulnerability, are identified by the *Unclass* attribute.

The lengths of the Tasmanian coastline, as mapped at 1:25,000 scale, that fall into these indicative coastal vulnerability categories are summarised in Table 1 following (determined from the digital coastal map *tascsthz_v2gda*).

It should be noted that, whilst indicative storm surge flood vulnerability areas have been determined for the entire Tasmanian coastline (previous page), in terms of other coastal hazards (listed on Table 1), only 84% of the Tasmanian coastline has been indicatively assessed as having either potential vulnerability to the hazards noted above, or as having minimal vulnerability (sloping rocky) shores. There remains a further 16% of the Tasmanian coastline, consisting of a range of other shoreline types, for which vulnerability – or lack thereof – to hazards relating to climate change and sea-level rise (other than storm surge flooding) still remains to be indicatively assessed. Many of these are minor or unusual shoreline types (e.g., cobble beaches with no significant sandy component – see Sections 2.9 & 4.3.8) whose vulnerability will need to be assessed on a site–specific basis.

Length (km) * (1:25,000 scale)	**Percentage Length ***	**Shoreline Type & Indicative Vulnerability**
6472[2]	100%	Whole of Tasmania (incl. Bass Strait islands and other major islands, but excluding Macquarie Island)
1259	19%	Minimal Vulnerability shores (sloping hard-rock shores)
1129	17%	Open coast sandy shores backed by low-lying sandy plains (potentially susceptible to erosion and significant recession with sea-level rise)
371 *	5.5% *	Open coast sandy shores immediately backed by bedrock: (potentially susceptible to beach erosion and loss with sea-level rise, but shoreline recession likely to be minimal over next 50-100 years, except where bedrock is only semi-lithified)
512	8%	Re-entrant sandy shores backed by low-lying sandy plains: (potentially susceptible to erosion and significant recession with sea-level rise)
185 *	3% *	Re-entrant sandy shores immediately backed by bedrock: (potentially susceptible to beach erosion and loss with sea-level rise, but shoreline recession likely to be minimal over next 50-100 years, except where bedrock is only semi-lithified)
25 *	0.5% *	Other sandy shorelines (potentially vulnerable to erosion but type unclassified)
141 *	2% *	Low profile soft clayey – gravelly shores: (Potentially vulnerable to progressive erosional recession)
213 *	3% *	Moderately to very steep soft clayey – gravelly or colluvial shores: (Potentially vulnerable to progressive erosional recession and to slumping or landslides)
258	4%	Soft muddy shores backed by extensive low-lying unconsolidated sediment plains: (Potentially vulnerability to significant change with sea-level rise, including significant erosional recession)
200 *	3% *	Soft muddy shores mainly backed by bedrock: (Potentially vulnerable to limited shoreline change except where bedrock is colluvium-mantled or is semi-lithified bedrock)
1216 *	19% *	Exposed hard-rock cliffed shorelines: (potential vulnerability to rock falls, collapse, slumping and cliff retreat)
143 *	2% *	Sheltered hard-rock cliffed shorelines: (lower potential vulnerability to rock falls, collapse, slumping and cliff retreat)
1045	16%	Remaining shoreline types not falling into any of the above categories (vulnerability unclassified)

Table 1: Total lengths of Tasmanian shorelines classified into the vulnerability categories described in this report. * Note that the individual shoreline type lengths and percentages sum to more than 100% because several coastal vulnerability types partly overlap (as indicated by *). For example, some sandy shores backed by bedrock are also prone to slumping, cliff rock falls or progressive erosion where the backshore bedrock is cliffed, or comprises semi-lithified Tertiary sedimentary rocks. Hence these and some other overlapping shoreline types are counted in more than one of the above categories.

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[2] Note that this total length is slightly greater than the total length of 6438 km calculated by Sharples (2004a) for the original version of this indicative vulnerability mapping. This is the result of the addition of a number of coastal tidal lagoons to the shoreline geomorphic map (*tascoastgeo_v4gda*) upon which the vulnerability map *tascsthz_v2gda* is based.

Recommendations
The indicative coastal vulnerability mapping provided with this report constitutes the logical first step in a broader strategic approach to coastal vulnerability assessment and management. Hence, the recommendations provided below are essentially aimed at progressing such a strategy to its subsequent logical stages:

Indicative (First Pass) Assessment:

- The indicative coastal vulnerability assessments provided with this report should be used as precautionary assessments of coastal vulnerability to guide coastal planning until such time as more detailed site-specific assessments are available for priority areas (see Section 3.2).

- In order to guide forward planning of developments in indicatively vulnerable coastal areas, it is recommended that planners and policy-makers give consideration to the most appropriate means of defining precautionary recession vulnerability areas or "envelopes" behind shorelines indicatively assessed as being vulnerable to erosion (see discussion in Sections 2.3, 4.3.3 and 5.0). Transparent recognition of the uncertainties in predicting actual future coastal recession rates will be important in managing coastal development.

- As new geological mapping of coastal areas by Mineral Resources Tasmania is completed, this mapping should be used to upgrade the *tascoastgeo* Shoreline Geomorphic Map, which should then in turn be used to upgrade the indicative mapping of slump-prone (and other) shoreline types provided as part of this indicative coastal vulnerability mapping (see sections 2.7 & 4.3.5),

Regional (Second Pass) Indicative Assessments:

- The exposure, wave energy and sediment budget attributes in the *tascoastgeo_v4gda* and *tascsthz_v2gda* map datasets should be upgraded and reviewed as described in Appendix 3, and incorporated into regional ("second pass") indicative assessments of Tasmanian coastal vulnerability areas (see Section 3.3.1). These datasets could be used to build on the approach to a "Second-Pass" assessment of Tasmanian coasts using a Coastal Vulnerability Index that has been initiated by Leaver (2005).

Site – Specific Assessments and modelling:

- The indicative coastal vulnerability assessment provided with this report should be used – in combination with socio-economic data and trends – to identify indicative coastal vulnerability areas that are under significant pressure from development or use, and hence should be priorities for site-specific vulnerability assessments (see Section 3.3.2). Pilot studies should be undertaken at a range of such sites to determine the scale and scope of site-specific investigations needed to improve understanding of the vulnerability of each site.

Shoreline Monitoring

- Programs to monitor the response of a range of Tasmanian shorelines to sea-level rise should be funded, encouraged and supported (see Section 3.4). Monitored shorelines should include indicative coastal vulnerability zones that are under development pressure, relatively undisturbed "benchmark" beaches, and a broad representative range of shoreline types distributed around the Tasmanian coast.

1.0 INTRODUCTION

1.1 *Purpose*

A robust body of evidence is now available which demonstrates that renewed global sea-level rise commenced about a century ago, and is continuing (see Section 1.3 below). A wealth of geological and geomorphic evidence shows that changes in sea level result in significant physical changes to shorelines – particularly softer sandy shores – as the coast adjusts to changing water levels (see further details in Section 2.0). These physical changes – including shoreline erosion and increased flooding – may be of sufficient scale as to expose coastal buildings, roads and other infrastructure to damage or loss, hence there is a need to identify coastal areas vulnerable to such changes in order to be able to effectively plan coastal developments.

Some coasts elsewhere in the world - such as the southeast coast of England and parts of the eastern US seaboard - have had a long history of coastal erosion problems because they are subsiding at geologically rapid rates, which has induced coastal erosion due to the rise in sea level relative to the land (in some such cases the subsidence is the result of glacio-isostatic adjustments following the melting of thick ice caps at the end of the Last Glaciation). The Tasmanian coast is tectonically stable by comparison, and whilst some coastal erosion has occurred in the past it has not been of such magnitude as to cause the problems which have traditionally plagued coastal developments in places such as southeast England. However, with the onset of renewed global sea-level rise Tasmania will begin to more frequently experience the types of coastal erosion problems that have previously been seen on less tectonically - stable coasts elsewhere. Indeed, Tasmanian coastal planners would be prudent to examine and learn from the past experiences of coastal planning authorities in places such as south-eastern England.

The mapping described by this report provides indicative identification of Tasmanian shorelines potentially susceptible to a range of key coastal vulnerabilities related to sea-level rise and climate change, namely increased storm surge flooding, shoreline erosion, slumping, and cliff rock-fall (Section 4.3). The project has also provided indicative mapping of a class of shorelines likely to be at minimal risk of significant physical impacts over the next century or so (Sections 2.10 & 4.3.7). It is the purpose of the indicative coastal vulnerability mapping described by this report to provide an initial or "precautionary" guide for coastal planning and management responses to sea-level rise in Tasmania.

This report also provides a discussion of approaches to making more detailed and site-specific assessments of coastal vulnerabilities related to sea-level rise and climate change, and identifies the further data collection that will be necessary to enable more detailed assessments to be carried out (Sections 3.0, 5.0, Appendix 3).

1.2 *Background*

This report describes and explains a digital map set that was developed during 2004 - 2006 to provide an indicative (or "first pass") identification of Tasmanian coastal areas potentially vulnerable to increased storm surge flooding, shoreline erosion, slumping, and cliff rock fall as a result of global climate change and sea-level rise.

This report and the maps it describes deal specifically with several (but not all) of the physical coastal geomorphic (landform) changes or impacts (including flooding) that are likely to result from climate change and sea-level rise; other changes, including biological and socio-economic impacts, are not addressed here, although many of these will be influenced by the geomorphic impacts.

The work described in this report builds on an earlier coastal vulnerability map which was prepared by Chris Sharples for three south-eastern Tasmania Local Councils (Clarence, Sorell and Tasman) during 2001 (Sharples 2001), as part of the preparation of a *South East Tasmanian Integrated Coastal Management Strategy*. The sandy shore vulnerability zones presented in that earlier work are essentially the same as those provided in the present indicative vulnerability zoning maps, however exposure to oceanic storms was used as a primary vulnerability factor in the earlier zoning. This approach has been modified in the present zoning, with exposure now being regarded as a *Locally Variable Vulnerability Factor* that was not used in preparing the indicative vulnerability maps provided with the present report, which are instead based solely on *Fundamental Vulnerability Factors*. It is now considered that exposure is better integrated during regional and site-specific vulnerability assessments (see Section 3.0).

1.3 *Climate Change and Sea-level Rise*

Global sea levels have varied repeatedly throughout geological time. During the last million years (and longer) sea levels have repeatedly risen and fallen by vertical distances of up to 130 metres or more, mostly in response to climatic changes associated with a succession of colder glacial phases ("ice ages") interspersed with warmer interglacial phases such as the present (Lambeck & Chappell 2001). During the last 140,000 years, sea level has only remained more or less steady for three periods of 5000 years or more, namely at the height of the last interglacial phase (circa 125,000 years BP), at the maximum intensity of the last glaciation (circa 20,000 years BP), and during the present interglacial phase since 6,500 years ago (Thom & Roy 1985, Lambeck & Chappell 2001). For the remaining roughly 70% of the last 140,000 years, sea level has varied almost continuously up and down over a vertical range of about 130 metres, in response to climatic changes (Lambeck & Chappell 2001). In the context of the last million years and more, the last 6,500 years of relatively steady sea levels has been unusual, yet it is during this same period that human society has developed writing and recorded histories. Consequently, human experience and recorded history have created a perception of sea level as something which remains constant, when in fact steady sea levels are more of an infrequent occurrence than the norm over timescales of millennia or longer.

However, based on a variety of instrumental (tide gauge) records and other data sources, there is now a strong consensus amongst oceanographers that global sea levels rose by 10 – 20 centimetres during the last century (Church & Gregory 2001, IPCC 2001). The indication from long period tide gauge records and other evidence in several parts of the world is that there was virtually no long term average change in global mean sea level from the first century AD to 1800 AD, but that renewed sea-level rise commenced during the 1800s (Church & White 2006). In Tasmania, analysis of historic 1840s tide gauge records from Port Arthur, together with recent tide gauge records from Port Arthur and Hobart, has established that sea level relative to the land in the south-east Tasmania region has risen by about 14 centimetres over that period, with most of the rise probably having occurred since the late 1800s (Hunter *et al.* 2003).

This represents a considerable acceleration of the rates of sea-level change that have occurred over the prior 6,500 years (since the global post-glacial marine transgression ceased and sea level stabilised at close to its present level: Thom & Roy 1985). Renewed sea-level rise during the last century is attributed primarily to thermal expansion of ocean waters and melting of glaciers, resulting at least in part from global warming and climate change associated with increased anthropogenic greenhouse gas emissions over the last few centuries (IPCC 2001). Church & White (2006) have shown that the rate of global mean sea-level rise has accelerated during the 20th Century, and a continued rise in global sea level, of between 9 and 88 centimetres by 2100 relative to the 1990 sea level, is now projected to occur over the next century (Church & Gregory 2001, IPCC 2001).

In addition to simple sea-level rise, global climate change is likely to affect a variety of other climate-related processes that impact on coasts. In particular, it is possible that increased frequencies of coastal storms of a given magnitude may occur, and this would further affect coastal flooding, storm wave erosion and other hazards (see further details in Sections 2.2 & 2.3).

1.4 *Limitations and Caveats*

The mapping of coastal areas potentially susceptible to hazards such as flooding and erosion which this report describes and accompanies, is an "indicative" or "first pass" vulnerability assessment only. That is, the maps accompanying this report indicate shorelines and coastal areas that *may* be susceptible to flooding, erosion and recession, both at the present time and as a result of ongoing sea-level rise and climate change. This indicative mapping is based on the best scale and quality of map data that is available as Tasmania-wide datasets, however such mapping is subject to scale limitations and in most areas represents no better than 1:25,000 scale mapping (see further details of the map sources used in Section 4.2).

In addition, the identification of areas potentially vulnerable to coastal hazards is based only upon the assessment of a small set of *fundamental vulnerability factors* which potentially pre-dispose a shore to a vulnerability to certain types of hazards. A wide range of other *regionally and locally variable vulnerability factors* may greatly increase or decrease the exposure of particular coastal areas to hazards; however most of these factors cannot be assessed at the state-wide level at which the indicative assessment described here has been conducted. These other factors must be assessed on a detailed, site-specific basis for each particular shoreline of interest (see Section (3.0) for further discussion of the significance of these differing levels of coastal vulnerability assessment).

As a result of these limitations, the indicative coastal vulnerability mapping described by and accompanying this report does not provide a definitive high-confidence assessment of coastal vulnerability at any particular coastal site in Tasmania. Rather, it provides – for the entire State of Tasmania – an indicative or "first pass" identification of shorelines and coastal areas which have the *potential* to be vulnerable to significant flooding, erosion and shoreline recession, either under present-day conditions or as a result of ongoing climate change and sea-level rise. Achieving a more confident assessment of the degree of vulnerability at any particular coastal site will require detailed mapping, assessment and monitoring of that particular site, taking into consideration a range of regionally and locally variable climatic, oceanographic, geological, geomorphic, topographic and other factors that apply to that site, and which have not been integrated into the indicative assessment maps accompanying this report.

1.5 *Acknowledgements*

This project was supervised and reviewed by the Sea Level Reference Group established by DPIW, comprising Dr Martin Blake and Mr Alasdair Wells (consecutive convenors, DPIW), Dr John Church (CSIRO Marine Research), Dr John Hunter (Antarctic Climate and Ecosystems Cooperative Research Centre, and University of Tasmania), Dr Werner Hennecke and Professor Richard Coleman (University of Tasmania), and Mr Mike Pemberton (Nature Conservation Branch, DPIW). A draft of the first edition of this report (Sharples 2004a) was also reviewed by Professor Bruce Thom (coastal geomorphologist, NSW). All of the above provided considerable critique and review comments on drafts of this report, which have been responded to in producing this final version. However, the responsibility for the final report, including any opinions expressed, remains that of the author.

In particular, I thank Dr John Hunter who gave considerable time to acquiring and statistically analysing tide gauge data from Tasmanian tide gauge stations, in order to extract recorded storm surge water levels for the Tasmanian coast. Tasmanian tide gauge records used in this project were obtained

from the National Tidal Centre, Bureau of Meteorology, which is the central repository for Australian tide gauge data. John Hunter provided considerable information and input for Sections (2.2) and (4.3.2) of this report (storm surge flooding vulnerabilities). Mike Pemberton also provided information on sand budgets and beach characteristics for a variety of Tasmanian shorelines, whilst Professor Richard Coleman provided access to wave height models for the Tasmanian coast, which relate to wave energies for different parts of the Tasmanian coast.

The sources of much of the geomorphic data used in this assessment are noted in Section (4.2) and Appendix 2. In addition, Frances Mowling (coastal geomorphology consultant and Ph.D. candidate, University of Tasmania) provided information on beach sediment budgets (i.e., progradation / stability / recession status) in many parts of Tasmania. John Corbett (GIS specialist, DPIW) provided useful advice on the spatial accuracy constraints of the Tasmanian 25m Digital Elevation Model (DEM). Colin Mazengarb and Clive Calver (geologists, Mineral Resources Tasmania) provided recent geological mapping and landslide hazard assessments that were critical in undertaking the indicative coastal slumping vulnerability mapping detailed in Section (4.3.5). I also wish to thank Kathryn Jerie (geomorphologist, DPIW) for revealing to me the secret of converting the (grid) DEM to (vector) shapefiles!

1.6 *Glossary and Conventions Adopted*

Risk Assessment Terminology – "Risk", "Hazard" and "Vulnerability".
The terms "risk", "hazard" and "vulnerability" are widely used in discussions of natural hazards such as the impacts of sea-level rise on coastal areas, however these terms are not normally used as synonyms, rather each has a distinct meaning. The usage adopted in this report complies with the current Australian usage of these terms, as adopted by a variety of workers including Geoscience Australia (see http://www.ga.gov.au/urban/factsheets/risk_modelling.jsp), Greve (2001) and others, and as used in many coastal vulnerability assessments overseas (e.g., Gornitz *et al.* 1994).

Used in this sense, *risk* is the product of both *hazard* and *vulnerability*, where the *hazard* is a physical process – such as sea-level rise or storm surge events – and *vulnerability* is the degree of exposure of things, such as geomorphic or ecological features, to the impacts of the hazards. The *risk* to valued assets at any location is then a combination of the *hazard* and the *vulnerability*[3]. This relationship is sometimes referred to as the "Varnes Risk Equation", where:

Risk = *Hazard* x *Vulnerability* x *Elements at Risk* (cited by Mazengarb 2005, p. 5)

In these terms, the assessment presented in this report and the accompanying mapping is essentially an assessment of coastal geomorphic (landform) *vulnerability* to the *hazards* of climate change and sea-level rise. The use of this vulnerability assessment to assess the *risks* to valued socio-economic or natural assets (for example, economically valued infrastructure, significant saltmarsh communities or prized beach environments) is a further stage of risk assessment which has not been undertaken here, but for which this indicative vulnerability assessment provides a basis.

[3] For example an asset on a coast vulnerable to the hazard of sea level rise (eg, a low sandy shore) is at high *risk* if sea level rise is occurring (*hazard* high x *vulnerability* high), but would be at low *risk* if sea level rise were not occurring (*hazard* low x *vulnerability* high). Alternatively an asset on a coast not vulnerable to sea level rise (eg, a moderately sloping bedrock coast) would be at low *risk* despite the occurrence of the hazard of sea level rise (*hazard* high x *vulnerability* low).

It should be noted that some workers use the term "sensitivity" in the sense that "vulnerability" is used here, and use "vulnerability" to mean the degree of risk that exists given the adaptive capacity of a system or society (e.g., Allen Consulting Group 2005, p. 19-20). However this report retains the usage of "vulnerability" expressed by the Varnes Risk Equation (above), which has been more traditional in geohazards work.

Technical terms and acronyms used in this report:
The following brief glossary provides brief explanations of some other selected key acronyms and technical terms used in this report.

ACCRETION Addition, deposition or accumulation of sediment.

AGGRADATION Upwards accumulation and growth of a sediment deposit.

AHD Australian Height Datum. Theoretically this datum is intended to lie at mean sea level, however the Australian Height Datum for Tasmania was established in 1983 at Hobart and Burnie at the mean sea level measured at those sites for 1972. Thus subsequent sea-level rise means that AHD now lies 0.038m below mean sea level at Hobart assuming an average linear rate of sea-level rise relative to the land of 1.2 mm / year for the south-east Tasmanian region since the late 1800's (Hunter *et al.* 2003).

BERM A distinct change of slope on a beach, marking the landwards limit of recent wave action. On some beaches the berm is composed of coarser material (e.g., cobbles) deposited during storms.

COLLUVIUM Slope deposits. Deposits of boulders, cobbles and finer material that have accumulated on slopes as a result of erosion and movement of material from higher levels. Many colluvial deposits in Tasmania formed under the more sparsely-vegetated conditions of the last glacial climatic phase.

DEM Digital Elevation Model. The 25m DEM of Tasmania, which was used in this assessment, is a digital map that comprises grid cells which each measure 25m on a side, and each of which is attributed with the altitude in metres of its central point above the Australian Height Datum (AHD). See further discussion of the 25m DEM of Tasmania in Section (4.2.2).

DPIW Department of Primary Industries & Water, Tasmania.

DPIWE The former Department of Primary Industries, Water & Environment, Tasmania. Now the Department of Primary Industries & Water (DPIW).

FLOOD – TIDE DELTA A sediment deposit (usually sand) that has accumulated in a coastal lagoon or re-entrant, at the landwards end of a tidal channel or re-entrant mouth through which tidal currents transport sand.

GEOMORPHOLOGY The study of landforms, their forms, genesis, development and processes.

GEOMORPHIC Pertaining to geomorphology.

GLACIAL PHASE A relatively cool period of Earth history during which significant expansion of glaciers and ice caps occurs, and sea level drops significantly. Multiple glacial phases have occurred during the last few million years. The Last Glaciation peaked about 22,000 to 17,000 years ago, and ended about 10,000 years ago.

HAZARD See discussion of risk terminology at start of this section

HOLOCENE The stage of geological time between the end of the Last Glaciation (about 10,000 years ago) and the present. The Holocene effectively equates to the present interglacial climatic phase.

INTERGLACIAL PHASE A relatively warm period of Earth History, between glacial phases, when glaciers and ice caps retreat and sea level rises significantly. The Earth is currently in an interglacial phase, and the last (previous) interglacial phase occurred around 125,000 years ago.

IPCC Intergovernmental Panel on Climate Change. An international organisation established in 1988 by the World Meteorological Organisation and the United Nations Environment Programme, for the purpose of reviewing and reporting on the current state of scientific understanding of and research into global climate change and its effects, including sea-level rise (see IPCC 2001).

LIST Land Information System Tasmania. Centralised Tasmanian Government land information (eg, topographic mapping) data system, operated by DPIW.

LITHIFICATION The geological processes whereby a soft sediment becomes a hard, tough rock over a period of time. Lithification processes include compaction of the sediment and the precipitation of chemical cements from groundwater.

LITTORAL DRIFT Movement of sediment (e.g., sand) along a shore in the near-shore zone, usually resulting from along-shore currents generated by wave action.

MHWM Mean High Water Mark, i.e., the mean of high water over a long period of time.

MRT Mineral Resources Tasmania (a division of the Tasmanian Department of Infrastructure, Energy & Resources). Includes the Tasmanian Geological Survey.

PLEISTOCENE The stage of geological time spanning most of the last 2 million years up until the end of the Last Glaciation 10,000 years ago. The Pleistocene has been marked by a succession of glacial and interglacial climatic phases which have caused sea level to repeated rise and fall over a vertical range of about 130 metres, and have exerted a strong influence on coastal landform development globally.

POST-GLACIAL MARINE TRANSGRESSION In this report, the period of relatively rapid and continuous global sea-level rise following the maximum intensity of the last glacial climatic phase (circa 22,000 to 17,000 years ago), when sea level rose by about 130 metres before stabilising close to its present level about 6,500 years ago.

PROGRADATION Seawards growth or accretion of a shoreline by addition of sediment, usually where the sediment budget involves a predominance of sediment supply and accretion over erosion.

QUATERNARY The period of geological time spanning most of the last 2 million years up to and including the present. The Quaternary Period is sub-divided into the Pleistocene (older) and Holocene (recent) stages.

RETURN PERIOD Average period of time between occurrences of a specified type of event. It is important to note that the return period is an average period only; i.e., a 50-year return period event does not necessarily occur regularly every 50 years. For example, two 50-year return period events could occur in one year, then not for another 100 years.

RISK See discussion of risk terminology at start of this section.

SEDIMENT BUDGET The balance between the supply of sediment (e.g., sand) to a shore and the erosion or removal of sediment from that shore.

SEMI-LITHIFIED Refers to sediments which are coherent and partly "turned to rock" (lithified) by processes of compaction and the precipitation of chemical cements by groundwater, yet remain softer and more erodible than a fully lithified rock.

SENSITIVITY See discussion of risk terminology at start of this section.

TALUS A variety of colluvium (slope deposits) typically comprising loose boulders and cobbles that have fallen, rolled or slid from an escarpment and accumulated below.

TRANSGRESSION In relation to the sea, a phase during which the sea rises or "transgresses" over formerly dry land.

TRANSLATION In coastal geomorphology: horizontal movement of a feature, for example of a coastal sand barrier as a result of erosion on one side and accretion on the other.

UNCONSOLIDATED,
UNLITHIFIED Refers to sediments that remain more-or-less loose or friable, not formed into hard rock by geological processes such as compaction and precipitation of cements from groundwater.

VULNERABILITY See discussion of risk terminology at start of this section.

2.0 COASTAL GEOMORPHIC VULNERABILITY TO SEA-LEVEL RISE AND CLIMATE CHANGE IN TASMANIA

This section describes the theoretical basis of the coastal vulnerability mapping that is described in Section (4.0) of this report. This section should not be construed as a description of Tasmanian coastal or shoreline types as such; rather, it describes a number of key coastal geomorphic vulnerabilities likely to affect, or increasingly affect, the risks to assets on the Tasmanian coast as a result of climate change and sea-level rise. The processes by which each vulnerable coastal type responds to coastal hazards are described, and the types of shoreline likely to be affected by each hazard are identified along with a list of coastal geomorphic characteristics which may vary the degree to which any given susceptible shoreline responds to that hazard. The following Section (3.0) provides an outline of general methodologies for assessing coastal vulnerability, and identifies the approach that has been taken to actually making an assessment of Tasmanian coastal vulnerability in Section (4.0) of this report.

2.1 *The Basis for Identification and Modelling of Coastal Vulnerability*

Coastal landforms, particularly "soft" shores such as sandy, muddy, clayey and gravelly coasts, are some of the most mobile and dynamically changing geomorphic (landform) environments on Earth. Even in the absence of sea-level rise and climate change, coasts can and do change their physical form significantly over relatively short periods. Such changes may be continuous and progressive (e.g., the ongoing long-term physical adjustment of shorelines to the post-glacial sea level that stabilised at roughly its present level a mere 6,500 years ago), or they may be episodic and non-linear (e.g., repeated major adjustments of sandy shores to occasional periods of more-frequent-than-usual storm activity). Human modification of shores and coastal processes, through construction of sea walls, groynes, and in many other ways, have also caused physical changes to shorelines – often in ways that were not expected – and many modified shorelines are continuing to adjust in response to such disturbances.

As a result, a wide range of coastal hazards including flooding and coastal erosion have posed risks to human coastal infrastructure and other assets throughout history, in many cases for reasons unrelated to sea-level rise. Some of the natural changes that have occurred to Tasmanian shorelines over the last 6,500 years – in the absence of significant sea-level rise – are noted in the following descriptive sub-sections of this report, and in many cases these changes pose ongoing risks for inappropriately-sited coastal development in Tasmania. It is important to be aware that sea-level rise and climate change are not the only causes of coastal hazards in Tasmania, however the renewed sea-level rise and climate change that has commenced over the last century or so adds a major new factor into the complex of natural processes determining coastal landform changes in Tasmania. In particular, sea-level rise and climate change are likely to increase or accelerate coastal flooding and erosion hazards where these have existed previously, and is likely to initiate new phases of erosion on some shores that were previously in equilibrium.

An extensive and robust body of scientific observations and theory show that changes in the mean level of the sea relative to the land, in particular a rise in relative sea level, may result in the initiation or acceleration of significant geomorphic (landform) changes in coastal areas. A number of coastal behaviour models have been developed to describe and predict the response of various types of shorelines to sea-level rise, and some of those models which are relevant to Tasmanian shorelines are described in following sub-sections.

A large body of scientific literature on the coastal geomorphic effects of sea-level rise now exists, and useful reviews have been provided by a number of workers, for example Bird (1993). Scientific models of coastal geomorphic behaviour in response to sea-level rise are based on at least three broad classes of evidence, namely:

1. *Direct observation and monitoring of geomorphic effects on coasts where sea level is rising relative to the land for reasons other than global sea-level rise.* The effects of relative sea-level rise have been observed in locations such as large subsiding deltas (e.g., the Mississippi delta: Bird 1993, p. 71), on coasts subject to subsidence due to groundwater extraction, in locations where glacio-isostatic adjustments have caused coastline subsidence (e.g., eastern USA south of New York:- Zhang *et al.* 2004; south-eastern England), and on the shores of large inland seas such as Lake Michigan (North America) which are subject to significant water level oscillations over periods of years and decades (e.g., Olson 1958).

2. *Interpretation of geological and geomorphic evidence of past sea-level changes*. The geomorphic effects of past phases of sea-level rise can be interpreted from the geological and geomorphic record, for example the beach ridges, marine sediments, wave-cut platforms and erosional shoreline escarpments inland of the present Tasmanian coast that were produced by higher-than-present sea levels during the Last Interglacial climatic phase circa 125,000 years ago (e.g., Bowden & Colhoun 1984, Chick 1971).

3. *Experimental simulations and theoretical modelling.* Coastal behaviour modelling based on first principles, and experimental laboratory tests using wave-tank simulations of sea-level rise (e.g., Schwartz 1965), provide a means of identifying potential geomorphic responses to sea-level rise. Computer simulations have been developed which provide a powerful means of investigating likely coastal responses to sea-level rise (for example, the *Shoreface Translation Model* of Cowell & Thom 1994, Roy *et al.* 1994 and Cowell *et al.* 1995).

Based on these sorts of evidence, the following sub-sections describe some (but not necessarily all) important classes of coastal geomorphic changes whose effects on Tasmanian coastlines are likely to become significant as a result of climate change and sea-level rise. These changes may be considered as "risks" because they are likely to expose existing and inappropriately-planned future coastal infrastructure to damage or loss in many areas.

For each type of hazard, the basic geomorphic characteristics which identify shorelines that may be vulnerable to (some unspecified degree of) impacts from that hazard are listed in the following sub-sections as *Fundamental Vulnerability Factors*. Additional geomorphic and environmental characteristics that may determine and modify the degree, pattern and rate of such impacts on a particular shoreline are listed as *Regionally and Locally Variable Vulnerability Factors*. The latter lists of site-specific variables are not necessarily exhaustive, but indicate the types of factors that must be taken into account in order to proceed beyond indicative identification (Section 3.2) of vulnerable shores, to more detailed assessments of the degree of vulnerability at any particular site (see Section 3.3).

2.2 *Storm Surge Flooding*

Water levels at the shoreline may be significantly higher during storm conditions than under normal weather conditions (see Figure 1). During storms involving a low pressure system a rise in water level known as a *storm surge* may occur due to a combination of low atmospheric pressures[4] and wind stress[5] on the water surface (Hubbert & McInnes 1999). Thus stormy onshore winds will increase water levels at the coast, with the greatest rise being possible if a high astronomical tide occurs while the maximum intensity of the low pressure system is crossing a coast.

In addition to the storm surge effect, the net effect of large breaking waves on the shoreline is to pile up water at the shoreline, so producing an addition rise in water level at the shoreline known as *wave set-up*. During severe events, wave set-up can contribute up to 0.5m of the total sea level (Hubbert & McInnes 1999). Finally individual breaking waves produce *wave run-up* to the highest point reached by storm waves on the coast, which can be considerably higher than the normal high tide level. Hubbert & McInnes (1999) suggest that wave run-up could typically be expected to contribute around 1.0 m to the mean sea level during extreme events, however this is dependant on wave energy and the shape and slope of the local terrain. Storms on the NSW coast during 1974, for example, produced wave run-ups significantly greater than 1 metre (Foster *et al.* 1975).

Where coastal topography is low-lying, with shorelines backed by flat coastal plains elevated only a few metres above the Mean High Water Mark (MHWM), storm surges can result in flooding of significant areas inland of the MHWM during storms associated with intense low pressure systems and onshore winds, especially where these co-incide with an astronomical high tide. Such coastal topography exists in a variety of locations around the Tasmanian coast, for example on some prograded sandy shorelines, spits and necks or "tombolos" linking areas of higher coastal ground, and on silty deltaic and estuarine sedimentary deposits. In these places, extensive, normally-dry coastal areas may extend considerable distances inland at heights only a metre or two above mean sea level. In some areas such as Lauderdale and Kingston Beach in southeast Tasmania, roads and developments including residential areas have been located on such low-lying coastal areas and are vulnerable to flooding during extreme events.

Rising sea levels and climate change have the potential to increase coastal flooding vulnerabilities associated with storm surges in two ways:

- As the mean sea-level rises relative to coastal landforms, a storm surge of a given magnitude (i.e., of a given rise above the mean sea level) will reach correspondingly higher topographic levels at the shoreline, and consequently will be able to flood to greater water depths and over greater areas to landward. Indeed, analysis of tide gauge records from Sydney and Fremantle indicates that storm surges reaching a given height have occurred more frequently (their return period has decreased) over the last half of the Twentieth Century as compared to the pre-1950 period (Church *et al.* 2004). This is considered to be mainly a result of sea-level rise allowing surges to a given height above mean sea level to reach higher topographic levels on the coast, and also to increased inter-annual variability.

- It is possible that future climate change may result in increased intensities of storms of a given return period (Pittock 2003, p. 68), in which case extreme storm surge flooding events may

[4] Falling barometric pressures produce a rise in water level at a rate of approximately 10mm per hectopascal fall in pressure; this is known as the "*inverse barometer effect*" (Hubbert & McInnes 1999).

[5] Wind stresses induce ocean currents which, if blocked by a coastal barrier, pile up against the coast to produce elevated sea levels by a process known as "*wind set-up*" (Hubbert & McInnes 1999).

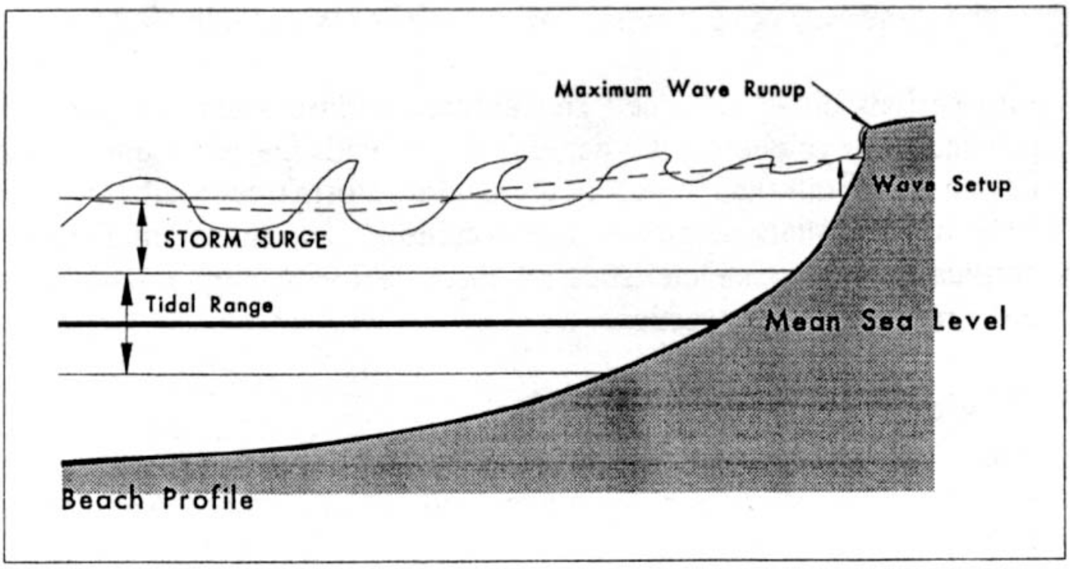

Figure 1: Contributions to extreme water levels at the coast. Diagram from McInnes *et al.* (2000).

become more frequent – and thus potentially do more cumulative damage to infrastructure and coastal ecosystems – than has hitherto been the case. No systematic increases in storm intensities have yet been detected in the Tasmanian region. However, it is known that storm activity in eastern Australia has been episodic during the Twentieth Century, with frequent large storms during some periods (such as during the 1970's in NSW: Thom & Hall 1991) and less storm activity in other periods. Historically, periods of more frequent and/or intense storm activity have caused increased flooding and coastal erosion (*ibid.*), and further such episodes are likely to occur in future, both as an element of the "normal" long term variability in storm activity, and possibly as an effect of long term climate change.

It is notable that the storm surge flooding vulnerability maps prepared during this coastal vulnerability mapping project commonly show little increase in coastal areas potentially subject to flooding under the higher sea-levels projected for 2100 as compared to present-day sea levels (see Appendix 1 maps, and discussion of the reasons for this pattern at the end of Section 4.3.2). Whilst this may give an impression that sea-level rise will generally cause little increase in the impacts of storm surge flooding on coastal areas, this is a misleading impression. The coastal flooding vulnerability maps depict only one dimension of the impacts of coastal flooding, namely the (horizontal) areas likely to be inundated. However there are several other effects of coastal flooding whose impact is likely to increase significantly as a result of mean sea-level rise and climate change, namely the depth of flood waters over the flooded areas, and the frequency with which storms of a given magnitude flood to those greater depths. These effects mean that the impact of coastal flooding in the future may increase significantly even on shores where the actual area of flooding increases only marginally. Thus, for example, if sea-level by 2100 rises by the maximum projected rise of 0.88 m (IPCC 2001), and the frequency of large storms increases, then properties which today are only rarely flooded to a depth of a few centimetres, will be more frequently flooded to depths of nearly a metre. This sort of change will have considerable additional impact on any infrastructure or assets in those flood-prone areas, even if there is little increase in the actual areas prone to flooding.

Fundamental Vulnerability Factors
The fundamental geomorphic characteristic pre-disposing a coastal area to storm surge flooding is:

- The presence of low-lying, low-profile coastal flats immediately backing the mean HWM.

For the purposes of the indicative assessment conducted during this project (see Section 4.3.2), coasts with a potential storm surge flooding vulnerability are taken to be those with significant low-lying backshore areas whose land surface lies within the height range of recorded storm surge events for the region (or within a range interpolated between the nearest available records), or which is likely to do so as a result of projected sea-level rise over the next century.

Regionally and Locally Variable Vulnerability Factors
More confident assessment of the *magnitude* and *extent* of storm surge flooding on a given low-lying coast – identified by an indicative assessment as having *some degree* of potential flooding vulnerability – requires a more detailed site – specific assessment and coastal behaviour modelling process (see Section 3.3.2) that takes into account any regional or local variables which may modify local storm surge magnitudes. Some (but not necessarily all) of the regionally and locally variable factors that must be integrated into a detailed coastal flooding model include the following:

- *Climatic factors*: wave climate (wave heights and energies) and the frequency and intensity of low pressure systems and resulting winds experienced in a particular region during storm events, which determine the degree of storm surge and wave set-up. In these respects, the western, northern and eastern coasts of Tasmania can sometimes be subject to quite different wave climates.

- *Coastal exposure and orientation* with respect to prevailing storm and wind approach directions on a given coast: more direct exposure to onshore winds and to the direction of the storm's movement allows a storm surge to pile up more water against the coast.

- *Sea floor topography (bathymetry)* is a very important factor: broad shallow sea beds (such as Bass Strait) can amplify a storm surge to a greater extent than steeper and deeper sea floors (Hubbert & McInnes 1999, CSIRO 2002).

- *Coastal plan-form*: channels and deep narrowing bays between headlands tend to funnel and amplify storm surges (Hubbert & McInnes 1999, CSIRO 2002), whereas on the other hand broad coastal re-entrants behind relatively narrow entrances (such as Pittwater, Bathurst and Macquarie Harbours) may attenuate storm surges by restricting the rate at which the storm surge water mass can enter the coastal re-entrant.

- *Local shoreline topography* will partly control the degree to which wave run-up can increase the height reached by water at the coast – steeper shoreline profiles will allow wave run-up to a greater height but only to a short distance inland, whereas a gentler shoreline profile will allow waves to run a greater distance inland, but only to a lower height as wave energy is dissipated over the longer run-up. In general, the area of potential flooding is increased as the landwards extent of very low-lying, low-profile ground increases. However, factors such as the presence of a high unbroken frontal dune ridge along a shore may limit the degree to which storm surge flood waters can inundate low-lying backshore areas protected by the dune.

- *Interactions with other local geomorphic and hydrological processes*: Storm surge flooding levels may be increased by interactions with other hydrological processes at certain coastal sites. An important situation may occur in and adjacent to the estuaries of flood-prone rivers:

under the scenario of a storm surge associated with a high rainfall event, a river flood pulse may occur due to increased catchment runoff. In the estuarine river reaches, the interaction between the storm surge and the river flood pulse may significantly elevate estuarine flood levels. The storm surge may also impede the river discharge, in effect causing the river flood pulse to "pile up" in the lower reaches of the river, so causing more flooding upstream of the coast than would otherwise have been the case.

Again, the duration of a storm and its relationship with tide level is very important, with the co-incidence of a storm peak with a high tide having the potential to produce higher floods than otherwise.

Tasmanian Examples

Storm surges have flooded many low-lying coastal areas in Tasmania during the Twentieth Century, in some cases closing roads and causing property damage. However, the records of such events are mostly anecdotal and there has been no systematic analysis of historical storm surge flood records for Tasmania.

Several areas of very low-lying residential land in the South Arm peninsula region, near Hobart, have been subject to storm surge flooding during the Twentieth Century. On the low-lying sandy neck at the northern end of this region, large areas of residential development at Lauderdale lie less than 2.0m, and in some areas less than 1.0m, above AHD. Alexander (2003, p. 285) records that residents along the canal running through the middle of the residential area had "problems" with floods during the 1960s and 1970s. Flooding in Lauderdale during 1967 and 1970 resulted in properties and buildings on South Terrace and Bayview Road (south side of the canal) being flooded to depths of "over a foot" in some places, and caused local residents to demand that the Local Government "solve" the problem (The Mercury Newspaper "Eastside News" 2nd Nov. 1967 (p.4), 29th Oct. 1970 (p.1), 5th Nov. 1970 (p.2)). There appears to have been a misconception that the flooding was due only to heavy rainfall and blocked drains, however on such low-lying land the significantly elevated sea levels resulting from storm surges would greatly hinder the effectiveness of any storm water drains.

DELM (1996, p. 16-17) and SDAC (1996, p. 7.65) reported that several storms during the late 1980s and early 1990s caused flooding at Lauderdale, with a 1994 storm closing the main South Arm road at Lauderdale, and another in 1991 washing debris across the road. During the 1991 storm, wind-driven waves were reported breaking on the driveway of the Lauderdale BP Service Station – on the landward side of the main South Arm Road – however the wind abated prior to high tide, resulting in less flooding than would otherwise have occurred (The Mercury, 7th August 1991, p. 1-2).

The nearest tide gauge to Lauderdale is the Hobart gauge, about 12 km to the west. The highest recorded tide at Hobart – caused by a deep low pressure system passing south of Tasmania – reached 1.32m above AHD on 25th July 1988 (see Table 2), and this event caused flooding at both Lauderdale and further south at Bicheno Street on the south side of Pipe Clay Lagoon (DELM 1996, p. 16). See Figure 3. At Bicheno St., some residential properties today lie 0.8 – 0.9m above AHD, and are thus vulnerable to flooding (DELM 1996, p. 16). Elsewhere in Tasmania, the same storm surge event flooded several homes at West Strahan (west coast) to above floor level, pushed water to the doorsteps of homes at Kingston Beach, covered waterfront reserves in Sandy Bay (including Marieville Esplanade), flooded through a house at Old Beach, covered part of the Huonville to Cygnet Road, submerged some Battery Point streets and flooded several basements on Hobart's waterfront ("The Mercury" newspaper, 26th July 1988, p. 1).

In areas such as those noted above, and many similar areas around the state, the fact that historical storm surge flooding has occurred in areas of current residential development, under conditions

Date	Predicted Tide (metres above AHD[6])	Maximum Actual Tide (metres above AHD[6])	Atmospheric Pressure (hectoPascals)
25th July 1988	0.66	1.32	976
6th August 1991	0.78	1.30	980
26th May 1994	0.76	1.31	982

Table 2: Hobart tide gauge records cited by DELM (1996, p. 16), SDAC (1996, p. 7.65) and The Mercury newspaper (26th July 1988, p. 1)[7] for three of the storm surge events which have historically flooded parts of Lauderdale (with cited figures adjusted to AHD). It should be noted that the extreme levels (relative to AHD) given in this table appear large compared with the 0.01% exceedance levels shown in Table 3 (Section 4.3.2) later in this report. This is partly due to the fact that Hobart (in common with other tide gauge sites in south-eastern Tasmania) exhibits sea-level oscillations of a period of less than one hour, which are presumably meteorologically-driven (Dr J. Hunter *pers. comm.*). Such oscillations, which were of approximately 0.05m amplitude during the three events of this table, cause the maxima in the table to be about 0.05m higher than the hourly-averaged values on which all 0.01% exceedance levels (Table 3) are based. Figure 2 below shows the tide gauge record (originally digitised every 5 minutes) for Hobart for the extreme event of 25th July 1988. The dots show the hourly-averaged data from which the 0.01% exceedance levels were derived. A further reason for the extremes shown in Table 2 to be higher than would be expected from the 0.01% exceedance levels is the under-estimate of sea level (typically by about 0.06m) which is common to the gauges where the vertical datum is poorly known, namely Hobart, Stanley and Granville Harbour (Dr J. Hunter *pers. comm.*); this is discussed further in Section 4.3.2.

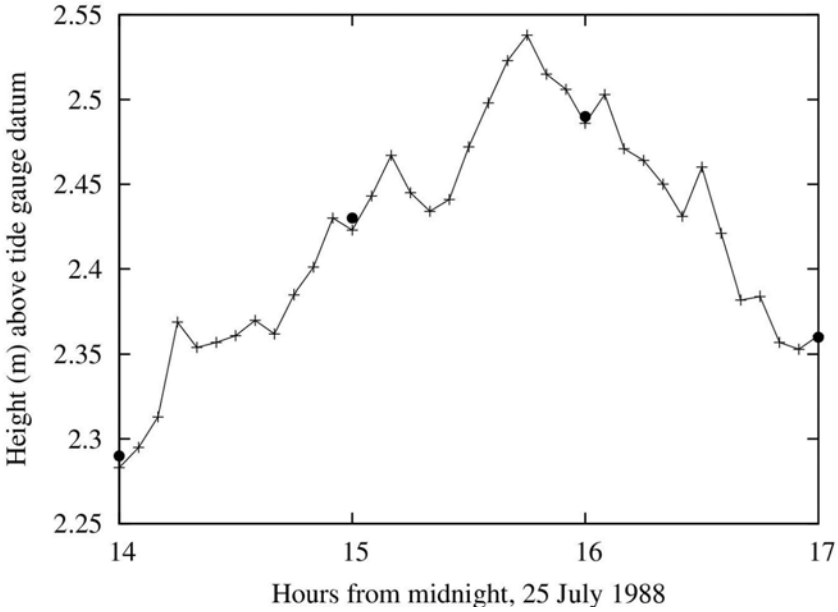

Figure 2: The tide gauge record for Hobart for the extreme high water event of 25th July 1988 (figure provided by Dr John Hunter). Continuous line and crosses are the 5-minute data from the tide gauge, dots are the hourly averaged data as used for the 0.01% exceedance levels described in this report (e.g., Table 3). The hourly-averaged tide levels are somewhat less than the maximum tide level for the storm surge event. Note that 1.219m must be removed from the extreme height above tide gauge datum (chart datum) to arrive at the equivalent height above AHD as used in Table 2 above[6].

[6] Tide levels were cited by DELM (1996) as levels above the Chart Datum (tide gauge datum). For Hobart, the Chart Datum was 1.219m below AHD prior to 30th May 1989, and 1.20m below AHD subsequently, due to a datum shift at the tide gauge (J. Hunter *pers. comm.*).

[7] DELM (1996) cited a maximum level of 2.55m above chart datum, however The Mercury cited 2.54m, a figure which is in accordance with actual record for the event as shown in Figure 2 above, and which has thus been used to calculate the 25 July 1998 maximum water level for Table 2.

associated with historical sea levels, highlights the increased flooding vulnerability for such areas under a scenario of sea-level rising by 0.09 – 0.88m between 1990 and 2100 (IPCC 2001).

Vulnerability Mapping

Indicative mapping of coastal areas potentially susceptible to storm surge flooding has been undertaken during this project (see Section 4.3.2). Historical tide gauge records have been used to determine water levels reached on Tasmanian coasts during 0.01% exceedance (roughly 2 year return period) storm surge events. Coastal areas below these levels – and thus potentially prone to flooding – have been indicatively identified using the 25m Digital Elevation Model of Tasmania which, although of variable accuracy and vertical resolution in different parts of the State, is the best digital topographic data set available at a State-wide level. Potential flood areas have been mapped for three scenarios, namely for 2004 sea level, 2100 minimum projected sea-level rise, and 2100 maximum projected sea-level rise. This indicative flood vulnerability mapping is provided as the *fldhz2004_gda*, *fldhz2100min_gda* and *fldhz2100max_gda* shapefiles (See Appendix sections A2.2.2, A2.2.3 & A2.2.4).

Because of the limitations in the accuracy of the base dataset, areas identified by this work as potentially susceptible to storm surge flooding should be regarded simply as potential vulnerability areas which are flagged as priority areas for more detailed site-specific topographic surveying and vulnerability assessment.

It should be additionally noted that the area of coastal land vulnerable to storm surge flooding, as depicted by this flood vulnerability mapping, does not capture all dimensions of coastal storm surge flood hazards. As noted above, increasing water depths during flooding (as a result of sea-level rise) and increasing frequencies of storms (as a result of climate change) may increase the risks associated with future coastal flooding beyond the level of risk implied by simple increases in the horizontal extent of areas prone to flooding.

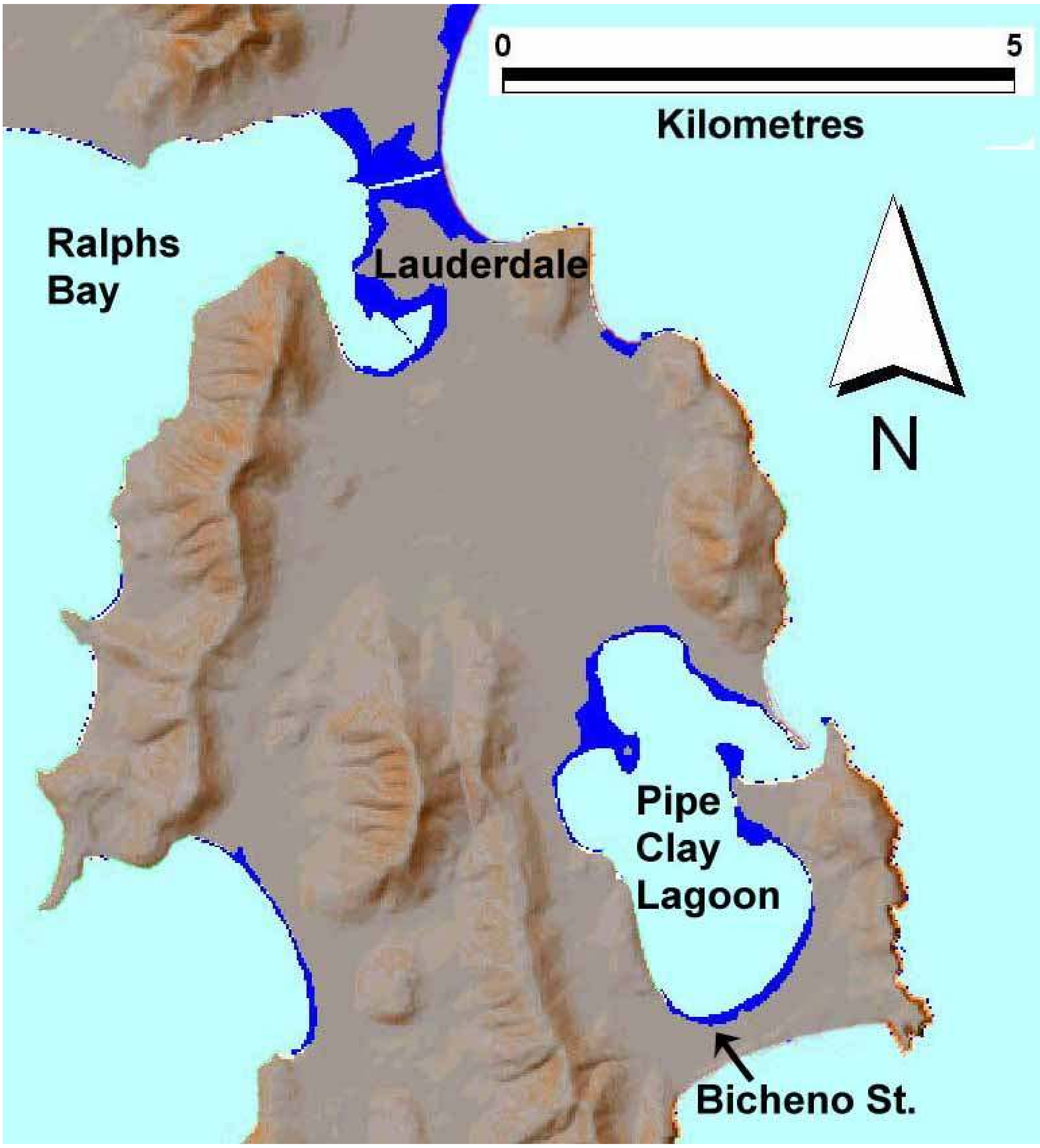

Figure 3: Map of Lauderdale and Pipe Clay Lagoon region, with dark blue indicating areas below the 1.32m AHD level. The highest recorded storm surge in southern Tasmania, on 25th July 1988, reached this level at the Hobart tide gauge (see Table 2 and Figure 2), hence this map indicates areas which could have been flooded on that date. Note however that the actual extent of flooding was not mapped on the day, and the storm surge could have reached a slightly different level at Lauderdale due to local variations in the vulnerability factors. This mapping of the extent of potentially – flooded areas is also subject to limitations on reliability inherent in the 25m Digital Elevation Model of Tasmania (2nd Edition, 2004), from which this map was prepared (see Section 4.2.2 discussion).

2.3 *Erosion and Recession of Open Sandy Coasts*

Sand grade sediments are generally defined to be those predominantly composed of grains ranging between 0.0625 to 2.0 millimetres diameter (Pettijohn *et al.* 1973). In the coastal environment, unconsolidated sediments within this grainsize range are highly mobile and small enough to be easily eroded and transported by waves, currents and winds that frequently act on most shorelines, in contrast to larger (pebble/cobble/boulder size) particles that are only moved by very energetic waves and hardly at all by wind. However, sand-grade sediments are also large enough to be rapidly dropped as wind or wave energy weakens, in the lee of a dune or in shallow subtidal zones below the surface zone of maximum wave energy, where they remain available for later remobilisation. This is in contrast to finer silt or clay particles which, once eroded from a shoreline, may remain in suspension for a long period and be transported considerable distances before settling out in deep, quiet subtidal waters to form sediment deposits that are unlikely to be significantly remobilised unless strong bottom currents are present.

Because of these unique grainsize-dependant characteristics of sand, sandy shorelines are highly mobile or changeable, and are capable of repeated alternations between erosion and accretion as sand is moved back and forth in response to changing conditions. Sand eroded from beaches and dunes during storms may drift alongshore in the surf zone, but generally is not transported a great distance offshore, and so can be returned to the beach and dunes under quieter conditions after storms. Such repeated onshore-offshore cycling of sand may occur over seasonal or longer periods in the course of the normal "cut-and-fill" cycle response of a beach/dune system to episodic storms. Similarly, beaches may "rotate" as longshore drift moves sand from one end of a beach to the other – and sometimes back again where cyclic climatic processes such as the El Nino Southern Oscillation (ENSO) result in cyclically variable wave climates (Short *et al.* 2000). These short term cyclic changes may be super-imposed on longer term changes to beaches and dunes which may occur in response to broader environmental changes, such as long term changes in the sediment supply to a beach, in mean sea level or in frequencies of storms (e.g., Thom & Hall 1991). Prolonged changes in such variables can lead to the onset of prolonged phases of net erosion along sandy coasts, or of net progradation (growth), depending on the nature of the change. Furthermore, when environmental conditions change, these can switch from an eroding to an accreting (prograding) state, or vice versa, or may oscillate around a stable equilibrium state

In contrast, most non-sandy shores (bedrock, gravelly, silty, muddy or clayey shores) will show only progressive net erosion in response to wave action (albeit at variable rates), unless there is an external source of sediment influx which exceeds erosion rates (for example, as on a growing muddy delta shoreline). In the absence of such external sediment supplies, any erosion of bedrock, gravelly or muddy shorelines is effectively permanent and cannot be reversed by the return of eroded material to the shore. Coarse material (pebble/cobble/boulder size) eroded from a shoreline by waves is quickly dumped in the near shore zone, but is too coarse to be moved back to rebuild the shoreline in the way a sandy shoreline can rebuild. At the other extreme, fine silts, muds and clays, once eroded from a shore, can remain in suspension for long periods and be transported to deep water where they settle out and are not available to be moved back to the shoreline.

In essence, sandy shores behave in a unique fashion compared to other shoreline types, because sand is both easily mobilised by wind, waves and currents, yet is not so mobile as to be easily removed from coastal geomorphic systems altogether. Amongst other things, this characteristic behaviour means that sandy shores have their own characteristic responses to sea-level rise which differ from the responses of finer- or coarser-grained sediment shores, or from those of hard rocky (bedrock) shorelines.

Tasmania possesses numerous sandy shores, derived ultimately from sandy sediments supplied to the continental shelf by rivers draining from extensive areas of highland glacial erosion (particularly to western, northern and south-eastern coastal areas), from fluvial (river) erosion (especially of highly erodible granitic terrains in north-east Tasmania), from biogenic carbonate deposition on the continental shelf (Colhoun in Burrett & Martin 1989, p.416), and from other sources such as local erosion of bedrock coasts. At 1:25,000 scale, Tasmania (including the Bass Strait islands and other major islands, but excluding Macquarie Island) possesses a total of 2222 kilometres of sandy shoreline (beaches), which is 34% of the total shoreline length, albeit this total includes narrow sandy shores backed by bedrock. However 1641 km (25%) of the Tasmanian coast consists of sandy beaches backed by dunes and low-lying sandy backshore deposits, on both open coasts and coastal re-entrant shores (see Section 4.3.3).

In Tasmania, sandy beaches are in high demand for coastal residential and other developments which, combined with their highly mobile nature, gives them a high priority for assessments of coastal vulnerability to sea-level rise hazards, such as coastal storms and resulting shoreline erosion.

Because of their highly mobile nature, long term erosion (or conversely accretion) of sandy shorelines can be triggered by a wide variety of changes in the coastal environment. Since at least the 1970s, if not earlier, over 70% of the world's sandy shorelines have been in a state of net erosion, while less than 10% have been prograding (growing) and only around 20% have been stable or oscillating around a stable equilibrium (Bird 1993, p. 52). Bird (1993, p. 53) lists 20 different factors which may cause beaches to erode, ranging from artificial interferences with sand movement caused by construction of groynes or seawalls, artificial stabilisation of dunes with grass, changes in water table levels, natural exhaustion of sand supplies moved by longshore drift, a rise in mean sea level, and others. Whilst sea-level rise is thus only one of many factors that can cause sandy beaches to erode, it is likely that the global rise in sea level which began roughly a century ago (see Section 1.3) is at least partly responsible for some of the beach erosion which has occurred globally during the 20th Century (although increasing artificial disturbance of beach systems in other ways has undoubtedly also been responsible for much erosion). It is also reasonable to expect that sandy shoreline erosion from this cause will become increasing significant over the coming decades as sea level continues to rise.

The Bruun Rule of Coastal Erosion with Sea-level Rise

The response of sandy shores to sea-level rise has been the subject of considerable scientific research globally for over four decades. Many studies of sandy coast erosion with sea-level rise have centred around a well-known scientific model known as the "Bruun Rule", however the current consensus of opinion is that, whilst probably essentially valid, the standard Bruun Rule is a greatly simplified or "idealised" model of coastal behaviour which needs to be supplemented with a variety of additional considerations before it can be used to realistically model the response of any real-world coastline to sea-level rise. The following discussion first outlines the Bruun Rule in its simple or "standard" form, then briefly notes the more sophisticated modelling procedures needed to allow the Bruun Rule to play its appropriate role in the larger problem of describing real-world coastal behaviour.

Bruun (1954, 1962) showed that sandy shores tend to respond to a rising sea level by eroding and receding landwards, in accordance with a process described by "The Bruun Rule" (Schwartz 1967, Bruun & Schwartz 1985, Bruun 1988). The geomorphic effect described by the standard Bruun Rule (see Figure 4) is essentially the following: as sea level rises, waves (especially storm waves) are able to penetrate further to landwards than previously, over the deepened near-shore zone; consequently they erode the beach – dune system to greater distances inshore than waves of the same magnitude could previously do, causing landwards erosional recession. The sand eroded in this way is withdrawn down the beach by storm wave backwash and dumped in the near-shore zone, building up the bottom in that area in such a way as to re-establish the near-shore profile that existed prior to sea-level rise (see Figure 4). In this simplified model, the near-shore sandy bottom profile is determined by the depth to which wave motion can move sand particles. Hence as sea-level rises so too does the effective wave base, creating additional sand accommodation space beneath it that allows the sandy bottom to build up accordingly with the sand eroded from the beach and dunes. As long as sea level

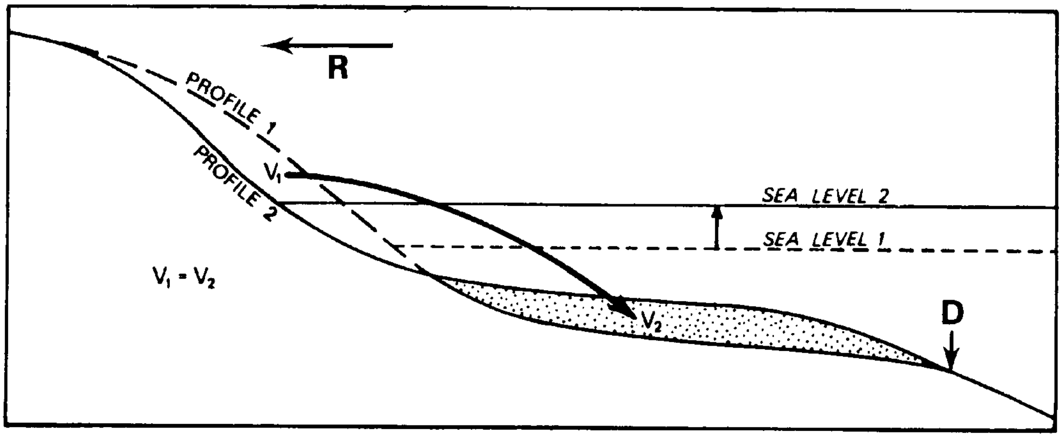

Figure 4: The standard Bruun Rule in its simplest form. From Bird (1993, p.57, Figure 29), whose original caption to this figure reads: "The Bruun Rule states that a sea-level rise will lead to erosion of the beach and removal of a volume of sand (v1) seaward to be deposited (v2) in such a way as to restore the initial transverse profile landward of D, the outer boundary of near-shore sand deposits. The coastline will retreat (R) until stability is restored after the sea-level rise comes to an end. The coastline thus recedes further than it would if submergence were not accompanied by erosion."

Figure 5: This beach in southeast Tasmania is a good example of the type of shoreline likely to respond to sea-level rise in the fashion described by the Bruun Rule: This is a sandy beach, directly exposed to oceanic swells and storms, and backed by an extensive low-lying plain infilled with unconsolidated sandy sediments to a depth below present sea level. Coastal dunes have developed on the sandy plain and may reach heights of over 10 metres above sea level, but are composed of soft unconsolidated sand and will be readily eroded in response to sea-level rise. Such coastal locations are in high demand for coastal development in Tasmania.

continues to rise, erosion and beach – dune recession may continue to progress landwards in this fashion until a more resistant substrate, such as lithified bedrock, is encountered.

Theoretical considerations, observations of shoreline erosion on coasts where water levels have changed significantly due to land subsidence or other causes (e.g., Zhang *et al.* 2004), and wave tank experiments (e.g., Schwartz 1965) have shown that whilst the degree of erosional recession of the shoreline may vary widely depending on a range of local variables, in a large proportion of cases sandy shorelines behaving in accordance with the Bruun Rule recede horizontally to a degree which is about two orders of magnitude greater than the degree of sea-level rise (Zhang *et al.* 2004). According to Bird (1993, p. 56) the standard Bruun Rule translates to a relationship in which horizontal recession is most commonly between 50 to 100 times the vertical rise in sea level (reflecting the most common range of substrate gradients). This widely quoted "rule of thumb" means that a one metre rise in sea level will typically lead to a horizontal recession of sandy shorelines of between 50 to 100 metres. However, as discussed further below, there are many situations in which local variables can cause a sandy shore to recede to much lesser *or* to much greater distances than are indicated by this generalised rule of thumb, and the appropriate recession factor at any particular site would only become evident after a detailed site-specific assessment.

The Bruun Rule primarily applies to sandy shores. It does not necessarily provide a good model of the response of bedrock, coarse sediment or very fine sediment shorelines to sea-level rise (Cooper & Pilkey 2004). As noted above, wave-eroded materials on such coasts have different mobility characteristics which cause them to be transported and deposited in ways which may differ significantly from the sandy-shore processes described by the Bruun Rule.

Application of the Bruun Rule to real coasts

The Bruun Rule in its simple or standard form (above) essentially describes the response of an idealised (simplified) sandy shore to one process only, namely sea-level rise. The Bruun Rule assumes a shoreline which is in equilibrium (neither gaining nor losing sand) prior to the onset of sea-level rise, and does not take into account a wide range of other oceanographic, climatic, topographic, geomorphic and geological variables which may modify a particular shoreline's response to rising seas. Few if any sandy shores in the real world are as simple as that modelled by the standard Bruun Rule, and many are subject to a variety of other processes whose effect on shoreline response to sea-level rise may modify or in some cases overwhelm the standard Bruun Rule effect (e.g., Pilkey *et al.* 1993, Jones & Hayne 2003, Cooper & Pilkey 2004)[8]. Non-equilibrium sediment budgets and the effects of longshore (littoral) sand drift are two of the major variables which can modify or overwhelm the standard Bruun Rule – style response of a coast to sea-level rise (Cowell *et al.* 1995a, Stive 2004,

[8] Some workers, e.g., Cooper & Pilkey (2004), have recently argued that the Bruun Rule should be abandoned entirely because it does not account for all the variables and processes that govern the behaviour of sandy shorelines during periods of sea level rise. However in the present writers opinion this is rather like saying that the Law of Gravity should be abandoned because it fails to explain complex phenomena such as aircraft flight, which depend not only on the effects of gravity but also on other factors such as thrust and aerodynamic lift (which counteract gravity). Similarly, the Bruun Rule remains useful provided it is clearly understood that it is an idealised conceptual model describing the effects of one process only – sea-level rise – on an ideally simplified sandy shore. So long as it is understood that modelling real-world physical coastal behaviour requires integrated consideration of all the additional processes and variables which affect a coast, then the Bruun Rule remains a very useful conceptual tool for understanding one of those processes in particular, namely sea-level rise (reductionism is not a dirty word, but rather is a powerful scientific tool provided its limitations are understood). In the writers opinion, much of the current argument over the validity of the Bruun Rule results from attempting to use it as a complete model of coastal behaviour, which it is not. If instead the Bruun Rule is seen as simply one process affecting shorelines in tandem with a range of other processes – some of which may in certain circumstances completely overwhelm the Bruun Rule effect – then it can usefully serve its appropriate scientific role as simply one important factor to be considered alongside a range of others when attempting to model the behaviour of shores subject to rising sea levels.

Zhang *et al.* 2004). Tidal current processes (e.g., within and near narrow coastal re-entrant channels) also significantly modify the response of coasts to sea-level rise (Stive 2004, Zhang *et al.* 2004), whilst Roy *et al.* (1994) showed that the response of a sandy coastal barrier to sea-level rise may vary considerably depending on the subtidal substrate slope. These and some other variables that modify physical responses to sea-level rise on sandy shores are listed below as *Regionally and Locally Variable Vulnerability Factors*.

Complex feedback processes between the various natural geomorphic processes affecting particular coasts mean that in some cases the Bruun Rule effects of sea-level rise may dominate a coasts behaviour, while in other cases the effects of sea-level rise may be swamped by other local variables. In the latter case, at one extreme relatively little change may occur, while at the other extreme a non-linear modification of previous coastal behaviour may result in significant changes that are quite different to the simple Bruun Rule effect. For example, there are situations in which the effects of littoral (longshore) drift and sediment budget may be such as to cause sandy shorelines to respond to sea-level rise by prograding (growing seawards) rather than receding. This is likely to be the case at the southern end of Ocean Beach (western Tasmania), where sand eroded from the northern parts of the beach (see Figure 6) is drifting southwards and accumulating at the southern end, which is consequently prograding and is likely to do so more rapidly in future as sea-level rise causes accelerated erosion and southwards drift of sand from the northern parts of the beach. Similarly, during the phase of rapid post-glacial sea-level rise that ended 6,500 years ago, many Australian coasts experienced a net shorewards movement of sand – opposite to that predicted by the standard Bruun Rule – because of the availability of very large quantities of sand on the continental shelf which greatly modified coastal sediment budgets and effectively negated the Bruun Rule under those particular circumstances.

In order to model the likely response of a specific stretch of coast to sea-level rise, then, it is necessary to produce a sophisticated model of coastal behaviour which incorporates not only the simple 2 – dimensional response of a sandy shore to sea-level rise described by the standard Bruun Rule, but which also takes into account the range of other variables and processes that also affect that particular shore. An example is the "Generalised Bruun Rule" outlined by Dean & Maurmeyer (1983), which highlights the differing responses to sea-level rise of sandy shores having different substrate slopes, and particularly the effect of this factor on sandy coastal barrier responses to sea-level rise. The latter consideration was one precursor of the more sophisticated Shoreface Translation Model (Cowell & Thom 1994, Roy *et al.* 1994 and Cowell *et al.* 1995). The GENESIS Generalised Shoreline Change Model (Hanson 1989, Young *et al.* 1995) is another widely discussed coastal behaviour model which incorporates a range of coastal variables. The *Flood Tide Delta Aggradation* & *Translation* models described in the following Section (2.4) are models of the response to sea-level rise of sandy shores within coastal re-entrants, which supplement the standard Bruun Rule with consideration of certain other coastal processes that are uniquely characteristic of coastal re-entrants dominated by tidal currents, but not of open ocean shores. Hanson *et al.*(2003) have provided a discussion of some twenty different models of shoreline behaviour, each of which is appropriate to modelling the future behaviour of certain types of shorelines under certain conditions.

Nevertheless, the standard Bruun Rule remains a useful concept in its own right because it highlights the influence on sandy shores of one particular coastal process, namely sea-level rise. Whilst sandy shoreline responses to sea-level rise will clearly be complex, and may not always result in erosion and recession, the Bruun Rule highlights the fact that erosion and recession is the typical response to sea-level rise that is to be expected on sandy shorelines, and it is a likely response that must be adequately anticipated in any useful precautionary coastal planning process. The standard Bruun Rule is arguably the most widely used model of shoreline response to sea-level rise due to the lack of other suitable models of similar simplicity, and provides a valuable precautionary and indicative assessment of coastal responses to sea-level rise provided the limitations of the standard rule are understood.

Rates of Sandy Shoreline Response to Sea-level Rise
An additional uncertainty in sandy shoreline response to sea-level rise is the *rate* at which shoreline erosion and recession will occur. Shoreline recession does not occur gradually as sea level rises, but rather occurs episodically during major storms when energetic waves can reach the back of the beach to cause erosion of beach and dunes. Thus there is a lag between sea level rising and a corresponding degree of erosion taking place. The lag will depend on the frequency and intensity of storms affecting particular coasts, and erosion can be expected to progress most rapidly on coasts receiving the most frequent large storms. In Tasmania, the west and southwest coasts receive the highest annual wave energies (see Appendix section A3.2) – and probably the most frequent intense storms – and it is on the west and southwest coasts that sandy shoreline erosion is currently most prominently in evidence (Cullen 1998, Pemberton & Cullen 1999). See also "Tasmanian Examples" below. However, records of major erosive storms on Tasmanian coasts during the 20th Century have only been sporadically (and mostly anecdotally) kept, hence it is difficult to predict the frequency or statistical return periods of storms large enough to cause significant coastal erosion as sea level rises. This uncertainty is increased by the fact that there has been significant inter-decadal variation in storm frequency in SE Australia during the Twentieth Century (e.g., the 1970s were a particularly stormy period on NSW coasts compared to later decades: Thom & Hall 1991), and by the possibility that climate change may cause changing frequencies and intensities of major coastal storms during the 21st Century (Pittock 2003, p.68).

Because of these uncertainties, projection of the rates at which Tasmanian sandy shorelines are likely to recede in response to sea-level rise will only become possible as better climatic modelling of likely future storm frequencies and intensities, and their inter-annual variability, becomes available for the Tasmanian region in combination with detailed site-specific modelling of the behaviour of particular beaches (Section 3.3.2), and as monitoring of changes on particular beaches begins to reveal actual trends (Section 3.4).

Fundamental Vulnerability Factors
This section (2.3) deals primarily with the vulnerability of open (ocean-exposed) sandy shores to the impacts of sea-level rise and climate change. A second major category of Tasmanian sandy shores, those within sheltered coastal re-entrants (eg, tidal lagoons), are likely to respond to sea-level rise in somewhat different ways due to the differing coastal processes to which they are subject, and hence have been treated separately in Section (2.4) of this report. In the light of the preceding discussion, three key factors (geomorphic characteristics) can be considered to provide an indicative identification of open ocean shorelines on which some degree of sandy coast erosion and recession as described by the Bruun Rule will be an important factor in the response of those shores to sea-level rise (see Section 3.2 & 4.3.3).

The vulnerable shores are those that are:

- predominantly composed of unconsolidated sand-grade sediment in the intertidal zone (i.e., sandy beaches and dune fronts);

- "open" coasts, exposed to oceanic swells and particularly storm waves (as opposed to estuarine or coastal re-entrant shorelines protected from oceanic waves but affected by other processes such as tidal currents which are not generally characteristic of open coasts); and

- backed by low-lying (low-profile) plains underlain by unconsolidated sandy sediments in the immediate backshore, which may include coastal dune systems or may be low plains without significant dunes. Where a sandy beach is immediately backed by hard bedrock rising above sea level, the beach may still erode, but further recession will be retarded by the hard bedrock.

The existence of a low-lying soft sediment plain behind the beach is necessary for there to be potential for erosional recession of the shoreline to proceed for significant distances to landwards, in the general fashion described by the Bruun Rule.

Regionally and Locally Variable Vulnerability Factors
However, assessment of the *degree*, *pattern* and *rate* of erosional recession – or other response to sea-level rise - at a given sandy beach, identified by an indicative assessment as having *some degree* of potential erosional recession vulnerability, requires a more detailed site – specific assessment and coastal behaviour modelling process that takes into account any local variables which may modify the "idealised" coastal behaviour described by the Bruun Rule (see Section 3.3.2). Some (but not necessarily all) of the regionally and locally variable factors that must be integrated into a detailed coastal behaviour model include the following:

- *Wave climate*: The amount of wave energy received on a particular coast, and especially the frequency and intensity of storms affecting a coast, will strongly control the rate at which shoreline erosion occurs (Thieler & Hammar-Klose 1999). There is considerable variation in wave climates between, for example, the western, eastern and north-northwest Tasmanian coasts (see Appendix A2.3.1 & A3.2).

- *Tidal Range:* On open coasts with a smaller tidal range, storm wave energies attacking the shoreline are concentrated within a smaller vertical range and hence are likely to cause more rapid erosional recession over a series of storms. With larger tidal ranges, storm wave attacks on shorelines over a series of storms are likely to be spread out over a greater vertical range (depending on the tidal stage at the peak intensity of each storm), and hence cause less cumulative recession (Thieler & Hammar-Klose 1999). Tidal ranges on different Tasmanian coasts vary from around 0.5m to over 3.0m.

- *Exposure*: The orientation and exposure of a sandy shoreline to the most important storm wave approach directions for that part of the coast will affect its susceptibility to erosion. The exposure of some open ocean beaches may vary along their length from sheltered (e.g., immediately in the lee of a protruding rocky headland) to moderately exposed (further along the beach from the headland) to highly exposed (still further away from sheltering headlands, and where the curving plan-form of the beach results in the most direct storm wave attack). The degree of erosion and recession is likely to vary accordingly along the length of such beaches. However, it is important to note that a shore relatively sheltered from the most frequent storm approach directions may also be relatively exposed to less frequent but still significant storm directions.

- *Shoreline plan form and configuration*: At the most local scale this variable is related to exposure: the plan form of bays may cause some parts of a beach to be more exposed than others (as noted above); embayment plan forms may concentrate wave energy in certain areas; and reefs, islands and intertidal shore platforms may act as breakwaters, giving more shelter to certain parts of a sandy shore than others.

  At a slightly broader scale, coastal plan form can strongly affect sediment budgets (see also below) by influencing the degree to which longshore drift can remove or add sand to a particular beach. Deeply embayed coasts may include beaches in different embayments separated by rocky headlands, between which little if any exchange of sand occurs such that each embayment beach has a closed or equilibrium sand budget. For this reason Cowell *et al.* (1995a) considered beaches in deep embayments to be more likely to respond to sea-level rise in the fashion described by the simple Bruun Rule, than beaches on long linear coasts where major littoral drift of sand can in some cases overwhelm the simple Bruun – style response to sea-level rise.

- *Beach/subtidal gradients and form (bathymetry)*: Steeper offshore gradients absorb less wave energy than gentle (dissipative) gradients, although gentler gradients may also result in increased storm surge heights. These characteristics may locally determine shoreline responses to sea-level rise. At a slightly broader scale, the subtidal substrate slope on a sandy barrier-type coast was shown by Roy *et al.* (1994) to strongly influence the physical response of sandy barriers to sea-level rise, with shallower gradients causing greater long term rates of barrier retreat.

- *Dune height and bulk*: Larger dunes take more wave energy to erode, resulting in slower beach/dune recession in response to a given level of wave energy. In Tasmania, the largest dunes are typically found on west and southwest coast beaches, which face very strong prevailing winds[9].

- *Sediment budget*: Many beaches have not been naturally stable during and prior to the Twentieth Century, but rather have been naturally losing or gaining sand for a variety of reasons related to ongoing coastal evolution processes. Where a beach has been naturally losing sand, existing erosion may be accelerated due to sea-level rise; on the other hand where a beach has been naturally gaining sand (prograding), erosion in response to sea-level rise may be slower, or the shoreline may even continue to prograde if the sediment supply is great enough. Shoreline erosion resulting from rising sea levels may also trigger non-linear changes to the sediment budget, as for example when foredune erosion caused by the rising sea level initiates dune blowouts, which cause dune sand to be blown inland and removed from the shoreline system. This process appears to be occurring at some southwest Tasmanian beaches such as Nye Bay and Towterer Beach (Cullen 1998), and may increase the vulnerability of those beaches to erosion as decreased foredune bulk allows recession to proceed faster (this is a classic example of the way in which complex feedback processes between different coastal processes may cause "non-linear" changes to the way a shore responds to sea-level rise).

- *Bedrock surface topography*: Sand thicknesses over bedrock in many Tasmanian coastal sand bodies (beaches and dunes) typically extend to at least 10m below present sea level (e.g., Cromer 1979, Cromer & Leaman 1980). Where this is the case, sandy shore erosion and recession may proceed unhindered. However, on some beaches hard lithified bedrock protrudes from the beach or rises above present sea level beneath dunes or backshore areas; where this is the case the potential for shoreline recession will be limited, depending on the actual topography of the bedrock surface, although sand may still be removed from the beach area (e.g., see Jones & Hayne 2003).

- *Extent of soft sediment deposits in backshore area*: The further to landwards low lying unconsolidated sediment deposits extend, the further erosional recession of the shoreline can potentially proceed inland. This is related to the concept of *accommodation space* (Nichols 1999, Fawcett 2004), which refers to the ability of a sandy shoreline system to migrate landwards as the coast recedes: such migration (or *translation*) can occur where areas of low-lying soft sediment provide accommodation space, but will terminate where a rising bedrock surface prevents further landwards translation of sandy landform systems.

[9] Many of these dunes are nonetheless eroding significantly – see "Tasmanian Examples" – since although the dunes have a very large bulk, they also face the strongest wave energies of any Tasmanian coasts.

- *Artificial modifications*: Existing artificial modifications such as groynes, seawalls, marram grass planting on dunes, etc, may modify erosion and sediment transport processes in a variety of ways, with consequent modification of Bruun-style shoreline processes.

Tasmanian Examples
Tasmania has numerous exposed sandy beaches exhibiting the fundamental vulnerability factors (above) characteristic of beaches potentially vulnerable to erosion due to sea-level rise. Many of these beaches currently exhibit erosion scarps at the back of the beach, and some are known to have been in a predominantly erosional state for some decades (e.g., most west and southwest coast beaches, Raspin's Beach (Orford), and others). It is likely that this erosion is at least in part a response to climate change and the current phase of global sea-level rise which began roughly around the late 1800s, however in the absence of long term beach monitoring data and associated studies, it is difficult to be unequivocal about the degree to which current Tasmanian beach erosion is due to these causes. Quantitative monitoring of beach profiles in Tasmania has only commenced in the last few years (Hennecke & Greve 2003, Hennecke *et al.* 2004).

Nonetheless, Hunter *et al.* (2003) have shown that the mean sea level around Tasmania (specifically, at Port Arthur in SE Tasmania) has risen relative to the land by about 14 centimetres since 1841, and most of this rise has probably occurred since the late 1800s. Using the simplified "rule of thumb" application of the Bruun Rule, which states that horizontal erosional recession of exposed sandy beaches due to sea-level rise can be 50 to 100 times the vertical sea-level rise (see discussion above), this suggests that sea-level rise since 1841 could have caused or be causing up to 7 to 14 metres of horizontal recession on some Tasmanian beaches.

Cullen (1998) observed that nearly all southwest coast Tasmanian beaches are currently eroding, with large active foredune erosion scarps. Airphoto evidence indicates that this erosion has probably been in progress since at least the 1960s (e.g., active blowouts triggered by foredune erosion are visible on 1961 air photos of Nye Bay[10]), and extrapolation of the seawards slope of exposed palaeosols (buried soil horizons) in some of the scarped foredune fronts suggest that recent landwards recession of the dune fronts may be of the order of 10 to 20 metres (M. Pemberton *pers. comm.*). This degree of recession is of the order that would be expected from sea-level rise over the last century (see above). The likelihood of sea-level rise being a major cause is reinforced by the fact that the south-west Tasmanian beaches receive the highest wave energies of any Tasmanian coast (see Appendices 2 & 3), and would thus be expected to show the erosional effects of sea-level rise earlier than other coasts. In addition, apart from global sea-level rise, geomorphic processes on most south-west beaches are effectively undisturbed by any other artificial human interference (Sharples 2003). Most of the beaches are located in isolated embayments with "closed" sand budgets that limit the potential for natural processes such as longshore drift to cause progressive beach erosion, but which are situations in which the standard Bruun Rule – style processes of erosion with sea-level rise are more likely to dominate coastal behaviour (Cowell *et al.* 1995a). For these reasons, on many southwest Tasmanian beaches there are few explanations available to explain the observed erosion other than sea-level rise and possibly associated climatic changes such as changed storm frequencies and intensities.

Progressive and ongoing foredune erosion and recession has also been occurring since at least the 1970s (and probably much longer) on the northern 25 kilometres of the 32 km long Ocean Beach, on Tasmania's central west coast (Banks *et al.* 1977, p. 46) (see Figure 6). In this case it is likely that the erosion is at least partly of natural origin, because a strong southwards longshore drift at Ocean Beach has probably been depleting sand supplies at the northern end of the beach ever since the supply of "excess" sand brought onshore from the continental shelf during the post-glacial marine transgression was exhausted by dune building and beach progradation. Many south-eastern Australian beaches

[10] Tas. Lands Department air photo T: 360-50, Tasmania South West Run 3, 16th February 1961.

Figure 6: Significant ongoing beach and foredune erosion at Ocean Beach (western Tasmania) was probably initiated by natural processes, but may be accelerating due to sea-level rise. This photo shows a section of the erosion scarp at Ocean Beach in 2003. The blocks of black peaty soil visible in this photo had recently collapsed from the erosion scarp. This peaty soil probably formed in a wet back-dune swale, indicating that at this site the entire former frontal dune, at least, has been removed by erosion in recent decades.

ceased prograding about 3000 to 4000 years ago for this reason (Thom 1974, p. 205-206), and some subsequently entered a prolonged phase of recession due to gradual removal of sand by longshore drift. It appears likely that this has been the case at Ocean Beach, where Banks *et al.* (1977, p. 46) estimated that by 1977 the northernmost end of the beach had receded by at least 150 metres from its former (mid-Holocene?) position. However, whilst the prolonged erosion of Ocean Beach appears to be primarily a natural phenomenon, anecdotal evidence from Strahan residents (adjacent to Ocean Beach) suggests that the rate of beach and dune recession has accelerated over the last few decades (see Figure 6). Such acceleration of erosion rates would be an expected result of sea-level rise. There is a need to monitor the recession of this beach in order to determine whether an acceleration of recession rates can be detected quantitatively.

On other Tasmanian coasts, beaches currently range from prograding in a few cases (e.g., the east coasts of King & Flinders Islands), to equilibrium or apparently receding beaches (see Appendix section A3.4). At Raspin's Beach (near Orford in eastern Tasmania), ongoing beach erosion and recession has been occurring since at least the 1940s (Steane & Foster 1993, Hennecke & Greve 2003). No satisfactory explanation for this erosion has been demonstrated, and a recent assessment of the erosion problem (Byrne 2000) did not consider the possibility of sea-level rise being at least partly responsible. However, given the lack of alternative explanations to date, and the fact that renewed sea-level rise has been occurring since the late 1800s, it is reasonable to postulate that sea-level rise may be at least partly responsible for the observed ongoing erosion. High resolution monitoring of this beach has recently commenced (Hennecke & Greve 2003), and it can be hoped that the data obtained will allow a better understanding of the causes of erosion at Raspin's Beach in the future.

Beach erosion has also been a long term problem at Roches Beach (Lauderdale) in south-eastern Tasmania, where many houses have been built only metres behind the beach, on or just behind the low foredune. An analysis of historical air photos from 1948 to 1984 was stated to have revealed no detectable net beach or dune front recession over that period (Pitt & Sherry and Foster, 1988, p. 3), although the degree of resolution of that analysis was not stated. However a vertical wave erosion scarp up to 2 metres high has now been present along much of the foredune front for well over 5 years, and has not exhibited significant natural wind-blown sand accretion rebuilding the dune front as would normally occur on an equilibrium beach in the course of the natural "cut-and-fill" cycle of beach erosion and accretion. Instead, the exposure of the roots of large trees in the scarp suggest a degree of erosion that has not occurred for decades previously, at least. As with Raspin's Beach, it is reasonable to postulate that observed erosion at Roches Beach may be at least partly due to sea-level rise, and not merely to cyclic "cut-and-fill" processes. However it will be difficult to be unequivocal about this until beach and dune monitoring has been in place for some years.

It is reasonable to infer that the erosional effects of sea-level rise are beginning to be seen on some Tasmanian beaches, especially those on the high energy west and south-west coasts. Whilst not all beaches are currently eroding – and in fact a few are prograding (see Appendix section A3.4) – this is likely to be due to the influence of some of the locally variable vulnerability factors listed above, which may over-ride the effects of Bruun-style sea-level rise effects in certain local circumstances.

Figure 7: This wave-eroded dune scarp at the back of a beach in south-east Tasmania has recently (2003 – 2004) begun to expose the roots of large trees that have been growing on the frontal dune for at least 20 or 30 years. The progressive undermining of the tree roots prompted the local government Council to remove the tree in late 2005 (right) before it toppled dangerously. This dune scarp has been progressively receding for at least five years now – and probably somewhat longer – with no significant rebuilding of the dune front as would be expected on an equilibrium beach in the course of the normal "cut-and-fill" cycle. Whilst monitoring of this shoreline has only commenced very recently, and it is not yet possible to unequivocally determine the cause of the erosion, this pattern of progressive shoreline retreat is typical of that which is expected to occur on sandy shorelines in response to the 14 cm of sea-level rise that has occurred on the south-east Tasmanian coast since the 1840s.

Vulnerability Mapping

Indicative or "first pass" mapping (see Section 3.2) of exposed sandy shorelines around Tasmania that are potentially susceptible to erosion resulting from sea-level rise has been undertaken during this project (see Section 4.3.3), and is provided using the *Sandyvuln* attribute of the *tascsthz_v2gda* map shapefile (see Appendix sections A2.2.1 & A2.3.3). This indicative mapping has been possible since available coastal geomorphic mapping (*tascoastgeo_v4gda*, Sharples 2006; see Section 4.2.1) is sufficiently comprehensive and robust as to allow confident mapping of shores having the three fundamental vulnerability factors (above) that characterise shores having this type of vulnerability. In particular, sandy shorelines are readily identifiable using aerial photography, and this has been done; the combination of available topographic and geological mapping identifies low-lying backshore areas infilled by unconsolidated sandy Quaternary-age sediments to a fair degree of confidence; and exposure to oceanic swells and storms is readily determined using topographic maps and available climatic information.

In contrast, no site-specific assessment and modelling of coastal erosion processes has yet been undertaken for any particular Tasmanian beaches (see Section 3.3.2), and although monitoring of geomorphic change on exposed sandy beaches and dunes in Tasmania is currently seen as a high priority (see Section 3.4), this work is only just beginning (Hennecke & Greve 2003, Hennecke *et al.* 2004).

2.4 *Modification of Sandy Coastal Re-entrant Shores*

A significant proportion (see Section 4.3.3) of Tasmanian sandy shorelines are located not on open oceanic shores, but rather within coastal lagoons or re-entrants which are connected to the ocean via a relatively narrow tidal channel or mouth. Coastal re-entrants, in the sense used for the purposes of this report, are coastal water bodies which may be kilometres across, but which are connected to the open sea either continuously or intermittently by a channel or mouth which is sufficiently narrow that tidal currents develop which are strong enough to transport sandy sediment and build a flood tide delta within the re-entrant in those cases where a sufficient sand supply is available (see Figure 8 for an example of a characteristic Tasmanian coastal re-entrant in the sense used here).

Coastal re-entrants as defined above are subject to a suite of coastal processes which differ in some respects to those of open ocean shores, and hence it can be anticipated that their response to climate change and sea-level rise will differ somewhat. Re-entrant shores are typically not directly exposed to oceanic swell and storm waves (other than at the re-entrant mouths or in the broadest types of tidal current-influenced re-entrants), but rather to (usually smaller) wind waves generated across the available fetch of the re-entrant water body. Such wind waves can however be sufficiently energetic to cause shoreline erosion if generated by strong storm winds. Small scale littoral (longshore) sand transport may occur on shores within re-entrants, due to wind waves, but there is generally no large scale littoral drift of sand. However, a key characteristic of re-entrants is that they are subject to tidal currents not found on most open ocean shores. A feature of many re-entrants is the accumulation of a large sub-tidal flood-tide sandy "delta" within the re-entrant mouth (see Figure 8), composed of sand derived from a variety of sources within and beyond re-entrants, and transported and deposited by tidal currents. Tidal currents may circulate within a re-entrant in complex ways which vary with the size, shape and depth of the re-entrant, and the tidal range of the coastal region concerned. Particularly where re-entrants have relatively shallow water, sand and other sediments may be transported considerable distances within the re-entrant by tidal currents, in ways not seen on open ocean shores. Where the re-entrant is the estuary of a large river, the river discharge may interact with the tidal currents to further complicate the currents and sediment movements within the re-entrant.

Most Tasmanian re-entrants, in the sense defined above, that have significant sandy shores are coastal lagoons or estuaries whose mouths are barred by a sandy barrier or spit (e.g., Pipe Clay Lagoon, Pitt Water, New River Lagoon, Forth River estuary, Anson's Bay (Figure 8), Macquarie Harbour). The discussion in this section is primarily concerned with this type of coastal re-entrant. A number of other types of Tasmanian coastal re-entrants do not have significant lengths of sandy shore within them, and hence are not the focus of the following discussion; these include re-entrants such as Bathurst Harbour (which has predominantly rocky shores and lacks a significant sandy flood-tide delta) and the Mersey River estuary (which has predominantly bedrock and muddy shores, rather than sandy shores). In the case of some relatively broader-mouthed Tasmanian coastal re-entrants, such as the Derwent River estuary, these share some of the characteristics of barrier-barred re-entrants, such as having a degree of tidal current activity and some sandy shores, but it is in some cases unclear whether they possess sandy flood tide deltas of sufficient scale to influence their behaviour in the ways described below. In lieu of further investigation of the behaviour of such broader coastal re-entrants, for the purposes of this indicative vulnerability assessment their sandy shores have generally been classified as "open" rather than "re-entrant" sandy shores.

Re-entrant shorelines in Tasmania may include a mixture of sandy shores, bedrock, muddy or clayey-gravel , and some re-entrants may include most of these shoreline types (e.g., Anson's Bay: see Figure 8). Some of these re-entrant shoreline types are currently eroding in Tasmania, which may be due to a number of causes including continuing adjustment to the last post-glacial marine transgression, present-day sea-level rise, or to other factors. This section deals specifically with the behaviour of soft

Figure 8: A typical Tasmanian coastal re-entrant, Anson's Bay in Northeastern Tasmania. This re-entrant is the Anson's River estuary, which has been barred by a large sandy barrier beach, leaving only a narrow tidal channel connection to the sea. Shorelines within the re-entrant range from hard bedrock, to semi-lithified gravelly-clayey alluvium, to soft erodible sand shores. Potential sediment supply for the flood-tide delta from river discharge and the gravelly NW shoreline is probably small in this case, hence if the delta aggrades to keep pace with sea-level rise (as predicted by the *Flood-tide Delta Aggradation Model*), then the main sources of sand for the delta will be derived from erosion of the ocean-facing barrier beach (transported into the re-entrant via tidal currents) and from erosion of the west-facing sandy shore on the east side of the re-entrant. (Vertical airphoto Project A111, Run 7E, photo 1274-53, original scale 1:42,000, photo taken 25/2/1997, copyright © DPIW).

sandy shores within coastal re-entrants, in response to renewed sea-level rise. The likely behaviour of some of the other re-entrant shoreline types is dealt with in other sections (2.5, 2.6, 2.7, 2.8, 2.10).

Over the last 30 years, considerable effort has been expended in studies of the geomorphic development of Australian estuaries, including the barrier-barred estuarine lagoons which many Tasmanian coastal re-entrants represent (Kench 1999). Changes in sea level have been the ultimate control on the position and form of Australian estuaries and of their various components, such as sandy barriers, central mud-filled basins, fluvial sediment deltas and flood-tide deltas, all of which may change and translate (move) both laterally and vertically as sea level rises (or falls). This implies that various components of coastal re-entrants, such as sandy barriers and flood-tide deltas, may erode in some parts and accrete (grow or prograde) in others as they respond to sea-level rise.

Bird (1993, p. 61) notes that as sea level rises, estuaries and coastal lagoons will initially tend to widen and deepen. However as noted below there will be a concurrent tendency for flood-tide sand deltas within re-entrants to grow upwards so as to keep pace with sea-level rise. Depending on available sediment supplies, tidal deltas and sandy barriers may simply grow and translate landwards as sea level rises, however where sediment supplies are limited this may occur at the expense of the erosion of some soft shores within the coastal re-entrant (see further discussion below). In some cases, erosional recession of the exposed seawards side of sand barriers enclosing coastal re-entrants, combined with erosion (rather than accretion and landwards translation) of their more sheltered (landwards) sides in order to supply sediment to an aggrading tidal delta, may lead to breaching of new entrance channels through the barrier, and could eventually destroy the barrier and expose formerly-sheltered re-entrant shores to direct oceanic wave action (Bird 1993, p. 61). In some circumstances, a new barrier might later grow further to landwards after sea level has stopped rising.

This section primarily deals with the likely response to sea-level rise of soft sandy shores within re-entrants. These form a distinct class in terms of their likely response to sea-level rise, both because of the distinctive behaviour of unconsolidated sandy shores generally (see Section 2.3 discussion), and because of the fact that due to complications in sub-tidal sand movement related to tidal and river discharge currents, the standard Bruun Rule of sea-level rise erosion (see Section 2.3) may not apply well, in an un-modified form, to sandy shores within re-entrants or in areas adjacent to their mouths (Stive 2004, Zhang *et al.* 2004).

Hennecke (2000) has provided a detailed study of two coastal behaviour models that have been developed to describe the response of erodible sandy re-entrant shorelines to sea-level rise. These models effectively provide a refinement of the Bruun Rule for coastal re-entrant situations. The two models are known as the *Flood-Tide Delta Aggradation Model* and the *Flood Tide Delta Translation Model*, and are briefly outlined as follows (after Hennecke & Greve 2003):

Flood Tide Delta Aggradation Model

This model is based on studies of the effect of relative sea-level rise on the (subsiding) Dutch Wadden Sea, and assumes that the surface of a (sandy) flood tide delta within a re-entrant will aggrade (accumulate sediment and grow horizontally and vertically) as sea-level rises, so as to maintain a constant water depth over the floor of the delta. This aggradation requires a supply of sediment, which may come from a variety of sources including river sediments discharged into the re-entrant, transport of sediments from adjacent open ocean shores into the re-entrant by tidal currents, and sediment eroded from shores within the re-entrant. Depending on the availability of sediment from the other sources, a greater or lesser degree of sandy shoreline erosion will occur within the re-entrant to make up any shortfall in the amount of sediment needed for the flood tide delta to aggrade so as to "keep up" with sea-level rise. Thus, in order to determine the amount of sandy re-entrant shoreline erosion predicted by this model as a result of sea-level rise, it is necessary to determine the amount of sediment available from the other sources, such as river discharge and adjacent open ocean shores.

However, the complex feedback processes characteristic of many sandy coastal environments mean that the quantities of sediment available from other sources may change with sea-level rise and climate change. For example, as a rising sea causes greater erosion of sand from the seawards face of a barrier beach (in accordance with the Bruun Rule), and a deepening tidal channel adjoining the barrier allows more of that eroded sand to be transported into the re-entrant to feed the aggrading flood-tide delta (Bird 1993, p. 62), then the demand for sediment derived from erosion of shores within the re-entrant could decrease rather than increase. In this situation, there might be little erosion of sandy shores within the re-entrant, but rather the sandy landwards (re-entrant) side of the barrier might prograde (grow) into the re-entrant while the seawards side erodes and retreats, leading simply to a landwards translation of the entire sandy barrier.

Flood Tide Delta Translation Model

The Flood-tide Delta Translation Model is a refinement of the aggradation model that is suited to more open re-entrant bays in which tidal currents and a flood tide delta are still significant factors (W. Hennecke *pers. comm.*). This model assumes that, as the delta aggrades with sea-level rise, it also migrates further landwards into the re-entrant as sea level rises. Beaches around the re-entrant shore may erode to provide the sand necessary for the flood tide delta in the bay to grow and translate with sea-level rise.

Work on applying coastal behaviour models such as these to Tasmanian coastal environments has only recently commenced (Hennecke & Greve 2003). Due to the sensitive dependence of these models on a range of sandy sediment sources to feed the flood-tide deltas in each coastal re-entrant, and the wide variability of such sources between re-entrants, it is not possible to provide estimates of likely degrees and rates of sandy shoreline erosion and recession in any given re-entrant without site specific studies of each particular re-entrant. Nonetheless, a clear implication of these models is that, in many cases, erodible sandy shores within coastal re-entrants in Tasmania are likely to show some degree of erosion and recession with sea-level rise, albeit it is likely that there will also be circumstances where a sufficient abundance of sand supplied to the flood delta from other sources could minimise or prevent sandy shore erosion within coastal re-entrants due to sea-level rise.

Fundamental Vulnerability Factors

In the light of the preceding discussion, three key factors (geomorphic characteristics) can be considered to provide an indicative identification of re-entrant sandy shorelines on which some (unspecified) degree of sandy coast erosion and recession, as modelled by flood-tide delta aggradation and translation models in particular, may be an important factor in the response of those shores to sea-level rise (see Section 3.2 & 4.3.3).

The vulnerable shores are those that are:

- predominantly composed of unconsolidated sand-grade sediment in the intertidal zone (i.e., sandy beaches);

- estuarine or coastal re-entrant shorelines typically protected from oceanic storm waves but affected by other processes including tidal currents which are not normally significant factors on open coasts; and

- backed by low-lying (low-profile) plains underlain by unconsolidated sandy sediments in the immediate backshore, which may include coastal dune systems or may be low plains without significant dunes. Where a sandy beach is immediately backed by hard bedrock rising above sea level, the beach may still erode, but further recession will be retarded by the hard bedrock. The existence of a low-lying soft sediment plain behind the beach is indicative of a potential for erosional recession of the shoreline for significant distances to landwards.

Regionally and Locally Variable Vulnerability Factors

Certain of the regionally and locally variable vulnerability factors determining the degree and rate of change likely to be experienced on open sandy coasts with sea-level rise and climate change remain relevant to re-entrant sandy coasts, whilst others are less relevant (see Section 2.3). In addition a number of other variables become relevant to sandy re-entrant shores.

Regional wave climate is likely to be less directly relevant to re-entrant shoreline erosion insofar as it refers to oceanic wave climates, from which most re-entrant shores are largely sheltered (although relatively wide-mouthed re-entrants may be affected to some degree). However, this factor will affect erosion of the seawards side of sandy barriers, which may influence the availability of sediment to aggrading flood-tide deltas within re-entrants and thus influence the requirement for sediment to be eroded from re-entrant shores to allow flood-tide delta aggradation (this relates to sediment budget variables: see below). Other variables which remain or become relevant to re-entrant shorelines include (but are not necessarily limited to):

- *Shoreline exposure to wave fetch within re-entrants*: The exposure of open sandy coasts adjacent the re-entrant mouth to oceanic storm waves is relevant to re-entrant processes to the extent that it may affect the erosion and mobilisation of sand from adjacent open coasts into the re-entrant mouth, and hence via tidal currents to the flood-tide delta within the re-entrant. However the erosion of sandy shores within the re-entrant itself will largely be effected by wind-waves generated across the fetch of the re-entrant water body itself, rather than by oceanic waves, and will thus depend on the size of the water body. Hence, the degree of exposure of sandy shores within the re-entrant to prevailing storm *wind* directions is also significant, as is the fetch of the re-entrant water body across which winds from that direction can build waves before they break on a sandy shore within the re-entrant.

- *Shoreline plan form and configuration; dune height and bulk; bedrock surface topography; extent of soft sediment deposits in backshore area*: Insofar as sandy shore erosion within coastal re-entrants is likely to proceed in ways generally described by the standard Bruun Rule, but with modifications described by flood-tide delta behaviour models (as described above), these shoreline characteristics are likely to control sandy shoreline erosion behaviour within re-entrants in much the same ways as have been described for open ocean sandy coasts in Section (2.3) above.

- *Substrate slope (bathymetry)*: As noted in Section (2.3), the subtidal substrate slope on a sandy barrier-type coast was shown by Roy *et al.* (1994) to strongly influence the physical response of sandy barriers to sea-level rise, with shallower gradients causing greater long term rates of barrier retreat. Since many Tasmanian sandy coastal re-entrants are barrier-barred lagoons, this variable will strongly influence the response of these re-entrants to sea-level rise.

- *Tidal Prism (tidal range and re-entrant size)*: The tidal prism is the amount of water exchanged in and out of a re-entrant mouth during a tidal cycle, and it plays a significant role in determining the strength of tidal currents within a re-entrant, and hence the degree to which they can transport and re-distribute sandy sediments within the re-entrant. The tidal prism is to a large extent determined by the tidal range on the relevant coasts, and by the area and volume of the re-entrant itself. Where the tidal prism is relatively small, some coastal estuarine lagoon mouths will occasionally be blocked by sand bars (as occurs in some eastern Tasmanian coastal lagoons), resulting in cessation of tidal current activity within the lagoon for a period.

  Note that the implication that larger tidal ranges (resulting in stronger tidal currents causing greater re-distribution of sand within re-entrants) may result in more significant sandy shore erosion within re-entrants, is the opposite to the situation applying to open ocean coasts (see Section 2.3 above). On open ocean coasts, where tidal currents are not a significant factor, smaller tidal ranges may cause more shoreline recession by concentrating storm wave energies within a smaller vertical range on the shore profile (Thieler & Hammar-Klose 1999).

- *Sand sediment sources and sediment budget*: As noted in the discussion above, the Flood-tide Delta Aggradation and Translation Models of coastal re-entrant sandy shoreline response to sea-level rise imply that the degree of sandy shore erosion that will occur within a re-entrant depends in part on the degree to which other sandy sediment sources are available, from sources such as river discharge and erosion of adjacent open-ocean sandy sources (via tidal currents). The available sediment sources and sandy sediment budgets will vary widely from one re-entrant to another, and thus the sediment budget for each re-entrant will need to be individually determined in order to make anything other than the broadest predictions about likely degrees and rates of erosion in particular re-entrants.

- *Artificial disturbances*: Artificial disturbances such as hard structures (seawalls, groynes, etc) and artificial stabilisation of available sand supplies (e.g., by marram grass planting) may affect sand sediment budgets and transport patterns within re-entrants, causing modification to the patterns of erosion that might be predicted from the Flood-tide Delta Aggradation and Translation Models (see example below).

Tasmanian Examples
Numerous Tasmanian coastal re-entrants contain erodible sandy shorelines that will potentially be subject to erosion as a result of sea-level rise, in accordance with the Flood-tide Delta Aggradation and Translation Models. Erosion is currently being observed on some of these, although detailed studies are yet to be undertaken to determine the degree to which observed erosion may be a response to sea-level rise that has already occurred to date.

Pitt Water – Five Mile Beach – Dodges Ferry
Significant sandy shoreline erosion is currently occurring in the large estuarine coastal re-entrant of Pitt Water in southeast Tasmania, at "Five Mile Beach" which is the northern (re-entrant) side of the Seven Mile Beach barrier spit that bars the mouth of Pitt Water (F. Mowling & M. Pemberton, *pers. comm.*). Sandy shoreline erosion has also been notable for some decades at nearby Dodges Ferry, adjacent the tidal-channel mouth of Pitt Water (Dobson & Williams 1978). Large sandy flood-tide deltas are present in Pitt Water (to seawards of the causeways), and the Flood-tide Delta Aggradation Model would suggest that erosion of Five Mile Beach is likely to occur with sea-level rise in order to supply sufficient sediment for aggradation of these (large) deltas. However, it is likely that an additional complicating factor is present at Pitt Water, in that large unvegetated mobile sand dunes on the eastern end of the Seven Mile Beach spit are also likely to have been significant sources of windblown sand for the flood-tide deltas during the Twentieth Century and earlier. Watt (1999) showed that the cover of the artificially-introduced dune-colonising weed marram grass (*Ammophila arenaria*) has expanded since 1950 from a coverage of only 15% of her study area on the Seven Mile Beach spit, to over 50% of the area. In the process, the proportion of bare sand dunes on the spit has diminished significantly. In the present writer's opinion, it seems highly likely that binding of the dunes by marram grass has significantly reduced sand supply to the Pitt Water flood tide deltas from that source, creating a sand budget deficit which has consequently been balanced by an acceleration of sandy shore erosion at Dodges Ferry and Five Mile Beach. Whilst erosion of these shores to supply sediment for the aggradation of the flood tide delta with sea-level rise is potentially to be expected under any circumstances, the artificial reduction of windblown sand supplied from mobile dunes on Seven Mile Beach spit has probably accelerated the erosion of these shores beyond the rates that would otherwise have occurred.

Vulnerability Mapping
Indicative or "first pass" mapping (see Section 3.2) of sandy shorelines around Tasmania that are potentially susceptible to re-entrant – style erosion resulting from sea-level rise has been undertaken during this project (see Section 4.3.3) , and is provided using the *Sandyvuln* attribute of the *tascsthz_v2gda* map shapefile (see Appendix sections A2.2.1 & A2.3.3). This indicative mapping has

been possible since available coastal geomorphic mapping (*tascoastgeo_v4gda*, Sharples 2006; see Section 4.2.1) is sufficiently comprehensive and robust as to allow confident mapping of shores having the three *Fundamental Vulnerability Factors* (above) that characterise shores having this type of vulnerability. In particular, sandy shorelines are readily identifiable using aerial photography, and this has been done; the combination of available topographic and geological mapping identifies low-lying backshore areas infilled by unconsolidated sandy Quaternary-age sediments to a fair degree of confidence; and location within coastal re-entrants is readily determined using topographic maps.

In contrast, no site-specific assessment and modelling of re-entrant-style erosion processes has yet been undertaken for any particular Tasmanian sandy shores (see Section 3.3.2), and although monitoring of geomorphic change on sandy shores and dunes in Tasmania is currently seen as a high priority (see Section 3.4), this work is only just beginning (Hennecke & Greve 2003, Hennecke *et al.* 2004).

2.5 *Modification of Muddy Estuarine and Deltaic Shores, and Salt Marsh Shores*

Whilst sandy shores are a distinctive class of soft sediment coast in terms of their response to coastal processes including sea-level rise and storms (Section 2.3, 2.4), Tasmanian coasts include several other distinctive classes of "soft" sediment shoreline, which respond to coastal processes somewhat differently to sandy shores. This section describes a class of sheltered, generally muddy, shoreline which is often (but not always) colonised by salt marsh vegetation, whilst another major class of soft shoreline (clayey-gravelly shores) are described in the following Section (2.6).

Soft fine-grained ("muddy" or "muddy-silty") unconsolidated sediment shores are common in sheltered Tasmanian coastal environments such as estuaries and coastal lagoons, although they are rare or absent on exposed oceanic coasts (where such soft and easily dispersible sediments would not survive or re-build after energetic storm wave erosion).

Muddy shores in Tasmanian estuaries are commonly deltaic sediment deposits that have accumulated from sediments brought to the coast by rivers. Typically such deltaic sediment shores slowly prograde (accrete sediment and build up) over time while sea level is steady and a river sediment supply is available. However erosion may occur in response to changes such as a rising sea, increased river discharge or decreased river sediment supply. As noted in Section (2.3), when a muddy shore erodes, the eroded material is not returned to the shore in the way sand can be, and the shoreline will progressively erode unless an influx of new sediment occurs (e.g., from a river) which is sufficient to counterbalance the rate of erosion[11].

Some Tasmanian muddy deltaic shores have been undergoing accelerated progradation over the last century or more due to artificially increased sediment supply from cleared and eroding agricultural regions in their river catchments. The response of these muddy deltaic shores to sea-level rise will depend at least in part on the degree to which poor agricultural and soil management practices continue to provide a supply of sediment which may or may not allow such muddy deltas to "keep up" with sea-level rise.

[11] It is likely that muddy shores will to some extent respond to sea level rise in the manner described by the Bruun Rule (see Figure 4), that is, sediment will be eroded from the upper shore-face and deposited offshore, raising the immediate offshore bottom so as to maintain a constant water depth. However, the Bruun Rule does not properly apply to muddy shores (Cooper & Pilkey 2004) because much of the muddy sediment (i.e., clays) eroded from the upper shore-face will not be dumped in the near-shore zone but rather will disperse into deeper water. Hence it is likely that a greater rate of muddy shoreline erosion and recession will occur, to build up the near-shore bottom sufficiently, than would be the case for an otherwise comparable sandy shore.

Figure 9: Soft muddy intertidal and supratidal flats at the seawards edge of the North West Bay River delta, near Margate in southern Tasmania. As is commonly the case, these soft muddy shores support saltmarsh vegetation. This muddy delta is thought to have grown considerably over the last century or more, in response to extensive land clearing and development in its catchment, causing phases of accelerated soil erosion which yielded significant sediment to the river.

Figure 10: Saltmarsh at Ralph's Bay, south-eastern Tasmania (see Section 2.5). This saltmarsh is growing on a pebbly sand substrate, rather than a muddy substrate. Whereas it is likely that in some areas saltmarsh will retreat and may even migrate landwards with sea-level rise to become a narrower fringe, in a location such as this – where potential for retreat is limited by the adjacent road – it is likely that the saltmarsh environment will simply disappear altogether as a result of only a few more centimetres of sea-level rise.

Not all muddy Tasmanian shores are deltaic deposits, however. Some muddy shores may accumulate in sheltered coastal re-entrants or estuaries as the result of local wave erosion of soft bedrock shoreline substrates such as clayey-gravelly semi-lithified Tertiary sediment shores. In these cases the muddy shorelines will typically comprise an intertidal zone of soft muddy sediment with a significant pebbly or sandy fraction, which will typically be backed by the clay-rich soft bedrock type in the backshore zone.

Salt Marsh

Many such sheltered muddy shoreline types are occupied by salt marsh, which is a coastal vegetation community (Harris in: Kirkpatrick 1991) that occupies a characteristic coastal geomorphic environment or niche, namely very low gradient shores in sheltered situations such as estuaries, lagoons and other coastal re-entrants. Salt marshes are typically highly saline environments exposed to frequent flooding or high tides. However Tasmanian salt marsh not only occupies muddy coastal flats, but may also occur on sandy or gravelly substrates (see Figure 10). Harris (in: Kirkpatrick 1991) estimated that 3,300 hectares of salt marsh occur on Tasmanian coasts, but it is most extensive along the highly indented south-east Tasmanian coast where many sheltered coastal situations exist (Kirkpatrick & Glasby 1981). Good vegetation mapping is available for Tasmania which identifies most of the important salt marsh environments on Tasmanian coasts (e.g., Kirkpatrick and Glasby 1991).

Salt marsh occupies the sort of coastal geomorphic environment that is generally occupied by mangroves on mainland Australian coasts (Harris in: Kirkpatrick 1991)[12], and it is likely that salt marsh environments in Tasmania will respond to sea-level rise in a fashion similar to mangroves elsewhere (Dr Joanna Ellison[13], *pers. comm.*). Ellison (1993, 2004) has shown that mangrove shorelines in a variety of locations are receding significantly in response to sea-level rise, especially in locations such as Bermuda where sea-level rise is being accelerated by land subsidence. Evidence from long stratigraphic records in mangrove environments shows that mangrove tidal flats expand significantly when sea level is steady, but recede to become narrow coastal fringes when sea level is rising (*ibid.*). In part the degree of recession of mangroves in response to sea level depends on sediment supply, with environments such as prograding muddy deltas better able to "keep up" with sea-level rise, however most mangroves show some degree of retreat in response to sea-level rise.

Studies are currently underway in Tasmania to assess salt marsh response to sea-level rise, and determine the degree to which these will respond in a fashion similar to geomorphically-related mangrove environments elsewhere (J. Ellison, *pers. comm.*). Thieler & Hammar-Klose (1999) considered North American salt marshes to be a coastal type particularly susceptible to changes resulting from sea-level rise. However, although Tasmanian salt marsh generally occupies a certain type of geomorphic environment (sheltered low-lying flood-prone saline coastal sediment flats), the differing characteristics of the sediment types making up the salt marsh substrate may result in differing responses of certain salt marshes to sea-level rise. Thus, it is possible that some Tasmanian salt marshes on sandy substrates (Figure 10) will behave similarly or identically to the sandy re-entrant shores described in Section (2.4) above, while other salt marshes on muddy substrates (Figure 9) may potentially behave rather differently due to the different sediment mobility characteristics of those substrates (see also Section 2.3 & Section 2.6 below).

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12 Mangroves occur as far south as the southern Victorian coast, but do not currently grow in Tasmania because of low frost tolerance. However, anecdotal rumours suggest that mangroves have historically been present as far south as King Island, and with climatic warming it is possible that they could again extend their southern range.

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Consequently, since "salt-marsh" is primarily a biological community type rather than a sedimentary or geomorphic type, the vulnerability mapping described in this report does not focus on "saltmarsh" as such – despite its frequent association with sheltered muddy shores – but rather focuses on the shoreline substrate types (muddy shores – this section, or re-entrant sandy shores – Section 2.4).

Fundamental Vulnerability Factors

The key characteristic identifying shores vulnerable to those changes characteristic of muddy shores is:

- Shorelines dominated by soft unconsolidated dominantly muddy – silty grade sediment in the upper intertidal zone (and usually extending into the subtidal zone).

In general, such shores will be found in sheltered estuarine or coastal lagoon situations. A pebble or sand fraction may also occur in the soft sediment, but muddy shores are characterised as being those where the muddy or silty sediment fraction is dominant. The muddy sediment may be only a zone of muddy sediment in the intertidal to sub-tidal zone, backed by harder bedrock backshores, or the muddy sediment may be backed by extensive soft muddy backshore ("supratidal") mudflats above the Mean High Water Mark. In both cases the soft intertidal zone sediment is prone to significant change with sea-level rise or other local changes, however where extensive supratidal mudflats are present in the backshore area there is potential for considerable erosional recession of the soft shores.

Regionally and Locally Variable Vulnerability Factors

Many of the regionally and locally variable vulnerability factors determining the degree and rate of change of muddy shores in response to sea-level rise and climate change are likely to be similar to those affecting sandy coastal re-entrant shores (see Section 2.4). However, there are several additional local or regional factors that may partly determine the response of muddy shores to sea-level rise. The factors likely to determine the response of muddy shores to sea-level rise include (but are not necessarily limited to):

- *Shoreline exposure to wave fetch and wave energy within re-entrants or estuaries:* As for sandy coastal re-entrants (see Section 2.4).

- *Shoreline plan form and configuration, bedrock surface topography, bathymetry, extent of soft muddy sediment deposits in the backshore area:* As for sandy coastal re-entrants (see Section 2.4).

- *Tidal Prism (tidal range and re-entrant size):* As for sandy coastal re-entrants (see Section 2.4).

- *River discharge:* Because many muddy shores are estuarine or deltaic deposits, the response of such shores to sea-level rise is partly determined by fluvial (river) processes. Changes in river water discharge (flow rate increase or decrease) may result in either erosion or accretion of sediment in estuaries, depending on the nature of the change. Such changes in river discharge can result from climatic changes, or from changing development and water use patterns in the entire river catchment area.

- *River sediment load:* Similarly, many muddy shores have formed as the result of deposition of fine fluvial sediments in deltas and estuaries, and hence changes in the sediment load carried to the coast by the rivers may cause either accelerated erosion or accretion of deltaic muddy shores. Increases in river sediment load can result from poor land use practices anywhere in the river catchment, and it is possible that where a river is carrying a significant sediment load, the resulting accelerated deposition of sediment in the delta region could counter-act a trend towards erosion resulting from sea-level rise.

Tasmanian Examples

In the overall context of the Tasmanian coast, muddy shorelines are a minor type, albeit notable insofar as they are significantly different in geomorphic and sedimentological terms from other more common shoreline types. Examples of sheltered muddy shorelines (of deltaic type) occur in sheltered estuarine reaches of the Leven, Forth, Mersey, Rubicon, Tamar, Coal, Derwent, Huon and numerous other Tasmanian rivers. In many of these cases, the muddy deltas are thought to have expanded considerably over the last two centuries in response to phases of extensive land clearance following European settlement of Tasmania.

Muddy – silty shores also occur in some large coastal (tidal) lagoons such as the northern (inland) part of Moulting Lagoon (eastern Tasmania). In the latter case the muddy shoreline sediments are probably at least partly of fluvial origin, but may be partly the product of weathering of underlying clay-rich Tertiary-age sediments.

Shoreline breakdown of exposed semi-lithified Tertiary sediment bedrock due to local wave action can produce a variety of shoreline sediments depending on the local nature of the Tertiary sediments and the degree of sediment winnowing due to wave action. In some places the resulting shoreline sediments are dominantly pebbly or sandy, but muddier shorelines of non-deltaic origin can also result from wave erosion of clay-rich Tertiary sediment bedrock, as occurs in some sheltered parts of the Pittwater coastal re-entrant near Hobart (see Figure 30).

Vulnerability Mapping

Muddy shoreline types have been indicatively mapped during this project using the *Muddyvuln* attribute in *tascsthz_v2gda* (see Sections 4.3.4, A2.3.3). A first pass assessment of this shoreline type was possible since data encoded in the available coastal geomorphic mapping (*tascoastgeo_v4gda*, Sharples 2006) identifies muddy shorelines.

Note however that the full extent of this shoreline type is still partly uncertain, since although some were mapped in the field, most of those recorded in the *tascoastgeo_v4gda*, and *tascsthz_v2gda* data sets were identified using air photos. This is problematical since muddy shores are difficult to distinguish from some fine sandy or even soil-covered bedrock shores on air photos. It is possible that some coastal re-entrant shores mapped as narrow sandy shores, or as soil-covered bedrock shores, may actually be muddy sediment shores (and *vice versa*). Extensive field mapping will be needed to refine the mapping of this coastal vulnerability type.

In addition to this uncertainty, some coastal estuarine re-entrants known to possess muddy shores (e.g., Leven and Forth River estuaries) are not shown on the indicative vulnerability mapping because the re-entrant shorelines they occupy were not included in the original version of the base geomorphic mapping (Sharples 2000) upon which the *tascoastgeo_v4gda*, and *tascsthz_v2gda* data sets are based, and have still to be so included.

2.6 *Progressive Erosion of Soft Clayey-Gravel Shores*

In addition to the very mobile sandy shores discussed in Sections (2.3) and (2.4), and the muddy estuarine/deltaic shores noted in Section (2.5), there is another characteristic variety of relatively "soft" Tasmanian shoreline which behaves very differently to either the sandy or the muddy soft shores. This further soft shoreline type comprises shores eroded into unconsolidated or only semi-lithified sediments of a generally clayey-gravel texture that are somewhat coherent, yet erosion – prone, and which are texturally quite different from the loose sands of sandy shores, or the very soft muds of muddy shores. These are typically deposits of fluvial (river) or lake sediments of Tertiary or Quaternary age. That is, in distinction to the sandy and muddy shores – which are typically shores of at least partly depositional origin, composed of unlithified sediments built up by geologically-recent coastal deposition processes – this other soft shoreline type has an essentially erosional origin as shores that have developed by marine erosion into older pre-existing semi-lithified sediments of non-coastal origin[14]. Examples occur on the north-west shoreline of Anson's Bay (NE Tasmania), the southern shore of Georges Bay (east coast), the north shore of Macquarie Harbour (western Tasmania), in the Tamar estuary, on parts of the Pittwater and Ralph's Bay shorelines near Hobart (see Figure 12), and at Cornelian Bay (Hobart; see Figure 11).

Some shores of deeply – weathered bedrock (such as deeply weathered basalt or dolerite) may also attain a similar coherent yet erodible clayey texture, and hence these can also be included in this shoreline vulnerability class despite having a somewhat different origin.

The shorelines considered in this section are essentially composed of soft but coherent mixtures of clay, mud, sand, gravel and sometimes coarser-grade material, which - although more coherent than sandy or muddy shores - are nonetheless much more erodible than hard bedrock shores. However, as discussed in Section (2.3) they cannot respond to wave erosion in the same fashion as a purely sand shoreline, that is, by rapidly attaining a "dynamic equilibrium" form which erodes during storms and is then rebuilt afterwards as eroded sand moves back to the beach and is blown onto the dune front in the "cut and fill" cycle. Rather, wave erosion of clayey - gravelly shorelines is progressive and irreversible (see Section 2.3) unless there is a significant influx of new sediment causing the shore to prograde (as on a muddy deltaic shore).

Tasmanian clayey-gravelly shorelines mostly commenced eroding when sea level reached roughly its present level 6,500 years ago (Thom & Roy 1985), and most former examples on exposed oceanic coasts have long since eroded into very low profiles and have become mantled by sands, forming sandy coasts of the sort described in Section (2.3). However in more sheltered estuarine and coastal re-entrant situations where they have been exposed to lower wave energies, it is likely that few such clayey-gravelly shores have yet eroded into a profile which is in equilibrium with sea level. Instead, many such shores in coastal re-entrants have the form of erosional scarps, and may include low vertical cliffs indicative of ongoing progressive erosion. Such cliffs are typically less than about 5 metres high since unlithified sediments are less capable of maintaining a high vertical face than is

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[14] In terms of the conventions adopted for the geomorphic mapping encoded within the *tascoastgeo_v4gda* and *tascsthz_v2gda* datasets (see Appendix 2), coastal substrates of non-coastal origin are regarded as "bedrock". Where these are relatively soft, as in the present case, they are classified as bedrock attribute "01" of the *Bedrock* attribute field (see Section A2.3.1).

Figure 11: Progressive erosion of unlithified Tertiary-age clayey gravels (fluvial sediments) in some parts of the Tasmanian coast is probably at least in part an ongoing response to the post-glacial marine transgression that ended only 6,500 years ago, however renewed sea-level rise is likely to cause accelerated erosion of some such shores. In this example, at Cornelian Bay (southern Tasmania), erosion of the Tertiary sediments also appears to have been exacerbated by artificial removal of much of the sand from the beach – which formerly protected the Tertiary sediments – some decades ago (Sharples 2003a).

Figure 12: Semi-lithified Tertiary-age sediments at Rokeby Beach (Ralph's Bay, southern Tasmania) are progressively eroding to the extent that in this case private freehold land (indicated by the collapsing boundary fence) is beginning to be lost to the sea. Note exposure of the tree root-ball: collapse of the tree is imminent. This progressive erosion is likely to accelerate with ongoing sea-level rise.

lithified bedrock[15]. Although many of the shores considered here have relatively low gently to moderately sloping profiles, where coastal profiles are moderately to very steep these eroding clayey-gravel shores may grade into slump-prone shores, as is the case on parts of the southern Tertiary-sediment shoreline of Georges Bay (St Helens) (as discussed in Section 2.7 below).

It is likely that most of these shores in relatively sheltered coastal re-entrants and estuaries have been progressively and more or less continually eroding for 6,500 years, and that even without renewed sea-level rise they would continue to do so for some considerable time into the future before they reached an equilibrium profile. However renewed sea-level rise is likely to result in an acceleration of the rates of erosional retreat of re-entrant clayey-gravelly shorelines, since the raised sea levels and resulting higher wave levels mean that these shorelines must now, in effect, "restart" the process of adjusting their profiles to a new, higher sea level. Furthermore, if storms of a given magnitude occur with increased frequency as a result of climate change, as is possible (Pittock 2003, p. 68), then this also will have the effect of accelerating the rate of progressive erosion of these shores.

There has been no study or monitoring of the rates of erosion and retreat of re-entrant clayey/gravelly shorelines in Tasmania, although this type of eroding shoreline has created concerns for adjacent infrastructure in several places. An example occurs on the north-west shore of Anson's Bay (NE Tasmania), where shacks have been constructed only metres behind an eroding shoreline scarp cut into semi-lithified fluvial (river) sediments. Significant erosional recession of the scarp has occurred at several points over the last few decades, and this recession is probably a part of the ongoing process of adjustment to the post-glacial sea level, although it may have been accelerated by renewed sea-level rise during the last century (Sharples 2002).

Fundamental Vulnerability Factors

The key characteristics identifying shores that will be prone to progressive erosional retreat as described in this section are:

- shorelines whose immediate backshore zones are composed of a semi-lithified or deeply weathered substrate ("bedrock") having a coherent yet erodible clayey-gravelly texture, where that substrate is exposed to wave erosion and is not mantled by sand or other coastal sediment.

This type of shoreline will typically if not always be found on coastal re-entrant shorelines sheltered from frequent oceanic storm wave attack. Where the near shore coastal profile is low and flat, these shores will mainly simply erode by means of wave attrition and small block falls, however as the coastal profile steepens, shores composed of the same clayey-gravelly substrates will become prone to larger slumps and landslides. These steeper slump-prone shores are described separately in the following Section (2.7), however it is worth noting that the two shoreline types actually grade into one another, their most important distinction being simply their profile (slope).

[15] Where vertical cliffs are present, this hazard category is distinguished from the "Sea Cliff" category (Section 2.8) because the cliffs in the latter category are developed in hard lithified bedrock rather than unlithified sediments. Sea cliffs in hard lithified bedrock commonly occur on exposed oceanic coasts, however cliffs in softer semi-lithified clayey-gravelly sediments are typically only present in the lower – energy environments of coastal re-entrants (for example, cliffs in Tertiary-age semi-lithified sediments occur along the north-eastern shore of the Macquarie Harbour re-entrant, and within the Derwent River estuary). On exposed oceanic coasts such substrates have mostly been long since eroded into a very low profile form and are now typically mantled by sand, as noted above.

Regionally and Locally Variable Vulnerability Factors

Since this category of shoreline occurs mainly in more-or-less sheltered coastal re-entrants, many of the regionally and locally variable vulnerability factors determining the degree and rate of change of these shores in response to sea-level rise and climate change are likely to be similar to those affecting sandy coastal re-entrant shores (see Section 2.4). Factors likely to determine the response of these shores to sea-level rise include (but are not necessarily limited to):

- *Shoreline exposure to wave fetch and wave energy within re-entrants or estuaries:* As for sandy coastal re-entrants (see Section 2.4).

- *Shoreline plan form and configuration, bathymetry, extent of soft clayey-gravelly sediment deposits in the backshore area:* As for sandy coastal re-entrants (see Section 2.4).

- *Tidal Prism (tidal range and re-entrant size):* As for sandy coastal re-entrants (see Section 2.4).

Tasmanian Examples

Some of the largest semi-enclosed re-entrants along the Tasmanian coastline are the topographic expression of major down-faulted graben basins (e.g., Macquarie Harbour, Moulting Lagoon, Pittwater, Ralph's Bay – Derwent Estuary). Many of these grabens were infilled with clayey and gravelly fluvial and lacustrine sediments during the Tertiary Period (circa 50 million years BP), and these sediments – still only partly lithified – are now commonly exposed as the shoreline substrate within these re-entrants. Several examples of shoreline erosion in these substrates threatening coastal developments and assets are noted in the preceding discussion (above). Texturally – similar sediments exposed in some coastal re-entrants have been mapped as putatively younger (Quaternary) sediments, for example on the north shore of Ansons Bay where shoreline erosion close to buildings is a concern. Nonetheless, these sediments are also of non-coastal (fluvial) origin, and are included as part of the clayey-gravelly shoreline type described in this section.

Most known examples of older bedrock which has weathered so strongly as to become a relatively soft clayey-gravelly substrate occur on moderate to steep coastal slopes, for example the deeply weathered basalts along parts of the Tasmanian north coast. Hence these shorelines mainly fall into the "slump-prone coasts" category described in the following Section (2.7). However, any examples of such softened bedrock located on low-profile coasts would probably respond to sea-level rise and coastal erosion processes in much the same way as the Tertiary-age clayey-gravelly sediments do.

Vulnerability Mapping

Soft clayey-gravelly coastal re-entrant shores prone to progressive ongoing erosional retreat even without renewed sea-level rise, and to accelerated erosion with renewed sea-level rise, have been indicatively mapped during this project (*tascsthz_v2gda* map shapefile, *Erosvuln* attribute code 10: See Sections 4.3.5, A2.3.3). This indicative mapping was possible since suitable base data for the indicative mapping of many such shores is available (e.g., comprehensive geological mapping of Tertiary-age semi-lithified coastal sediments is available for the whole of Tasmania and is generally reliable).

However, detailed geological and geomorphic mapping has not been undertaken along all Tasmanian coastal re-entrant shorelines, and it is likely that some further shores exposing similar sediments - like the putatively Quaternary-age clayey-gravelly sediments at Ansons Bay – will in future be identified. Thus, future field mapping and upgrading of the base data in the Shoreline Geomorphic map of Tasmania (*tascoastgeo_v4gda* (Sharples 2006)) and in *tascsthz_v2gda* (Appendix 2) will probably result in the identification of some further examples of this shoreline vulnerability category.

2.7 *Slump-prone Shores*

Certain moderately- to steeply – sloping (or even cliffed) Tasmanian shorelines are cut into materials prone to slumping and landslips. Such shorelines occur on both open oceanic coasts and within sheltered coastal re-entrants, and include shores cut into Tertiary-age basalt colluvium (slope deposits), semi-lithified Tertiary-age sediments (as described in Section (2.6) but predominantly on steep coastal profiles), and intensely fractured and/or deeply weathered bedrock including some Tertiary-age basalts, Jurassic-age dolerites and Permo-Triassic age sedimentary rocks. These shores represent locations where steep mass movement - prone shores are adjusting to the post-glacial sea levels of the last 6,500 years by slumping in response to ongoing wave attack and erosion at the toe of the steep coastal slopes. In most cases these slopes have probably been episodically slumping throughout the last 6,500 years, and are continuing to do so since, in most cases, they have not yet reached a stable profile form with respect to post-glacial sea levels.

As is the case with lower profile shores of clayey-gravelly substrates (Section 2.6 above), slump-prone shores are unable to "re-build" in the way that sandy shores can potentially do, and so are mostly in a state of progressive and irreversible retreat due to a combination of progressive wave erosion at the toe of the coastal slopes and consequent slumping at higher levels on the coastal slope (see Figure 14).

Examples of this type of landslip-prone shore include slumping coastal scarps on steep Tertiary-age sediments at Taroona (Hobart) and on the southern shore of Georges Bay (St. Helens) (see Figure 14), actively slumping coastal slopes on fractured and weathered Permo-Triassic sedimentary bedrock at High Yellow Bluff (see Figure 15), actively slumping fractured and weathered dolerite coastal slopes on parts of the Tasman Peninsula coast, and Tertiary-age basalt colluvium slopes at Boat Harbour (north west Tasmania – see Figure 13).

Boat Harbour provides a good example of the coastal vulnerability associated with slump-prone coastal slopes. Here, a thick apron of ancient basaltic landslide deposits (colluvium) mantles the coastal escarpment (which itself originated in part as an uplifted palaeo-shoreline of Last Interglacial age). These landslide deposits probably largely formed as inland terrestrial landslide deposits under the more arid and sparsely vegetated landscape conditions of the Last Glaciation, however subsequent to the post-glacial marine transgression wave attack has been eroding into the toe of the colluvial deposit apron, forming a short steep coastal colluvium scarp immediately above a sandy beach that extends to the high water mark (Coffey 2001). The toe of this scarp is exposed to wave attack during storm surges, causing toe erosion and over-steepening of the scarp, and several landslides and slump movements have occurred in and immediately above the scarp during the Twentieth Century (Coffey 2001). Although some of this slumping may have been triggered by human disturbance, the coastal scarp cut into the colluvium is very steep in places and is unlikely to have yet reached a stable profile form with respect to post-glacial sea levels.

As is the case with progressively-eroding clayey/gravelly shores (see Section 2.6 above), sea-level rise is likely to accelerate the existing episodic slumping of steep landslip-prone coastal slopes. This is likely to occur as higher sea levels allow storm waves to attack higher up the shoreline profile, initiating wave erosion of slump-prone shoreline materials not previously directly exposed to wave attack, and causing the shore to "re-start" the process of adjusting to a new, higher sea level by slumping. Furthermore, if storms of a given magnitude occur with increased frequency as a result of climate change, as is possible (see Section 2.2, & Pittock 2003, p. 68), then this also will have the effect of accelerating the rate of progressive erosion and slumping of these shores. Finally, an additional factor may occur as a result of more intense winter rainfalls which CSIRO climatic modelling suggests may occur in Tasmania in the future as a result of climate change (CSIRO 2001). Water saturation (through heavy rainfall) of slump-prone materials is a key trigger of landslides, and increased intensity of winter rainfalls may lead to more frequent occasions when unstable coastal

Figure 13: A coastal colluvium deposit rising from the back of a beach in northern Tasmania. The coastal scarp shown is an old basaltic landslide deposit of Last Glacial Phase age. Although vegetated and not as active as the coastal colluvium shown in Figure 15, sea-level rise will allow storm waves to erode the toe of this deposit, potentially leading to re-activation of the old landslide deposit. Note that old vegetated colluvium deposits such as these may be difficult to distinguish from bedrock coasts on air photos, but nonetheless are likely to be prone to increased instability resulting from sea-level rise.

Figure 14: Progressive erosional retreat and slumping of a steeply sloping shoreline in Tertiary-age semi-lithified clayey gravels of fluvial origin, on the south shore of the Georges Bay coastal embayment (St. Helens, east coast Tasmania).

slopes - already over-steepened by increased wave attack at their toes - will reach a threshold of water saturation leading to slumping.

Fundamental Vulnerability Factors
The key characteristics identifying shores that will be prone to slumping and progressive erosional retreat as described in this section are:

- shorelines whose immediate backshore zones are composed of unconsolidated slope deposits (colluvium), or of a semi-lithified, deeply weathered or intensely fractured substrate (bedrock), where that substrate is exposed to storm wave erosion and is not mantled by sand or other coastal sediment.

  and;

- shorelines having a moderately-angled to steep (or cliffed) coastal profile rising directly from the zone of storm wave attack (slumping typically occurs on slopes steeper than 20º, however susceptibility to slumping varies with different substrate materials and other local conditions, so that slumps can occur on slopes much gentler than 20º in certain circumstances: Mazengarb 2005).

Shores prone to slumping may occur either on the open coast or in sheltered re-entrants; even though sheltered re-entrants may not receive the full force of oceanic storm waves, the smaller wind-waves generated across the fetch of a re-entrant such as Macquarie Harbour or Georges Bay are energetic enough to erode the toes of shoreline slopes sufficiently to trigger slumping (see Figure 14).

Regionally and Locally Variable Vulnerability Factors
Many of the regionally and locally variable vulnerability factors determining the degree and rate of erosion of slump-prone shores, particularly in response to sea-level rise and climate change, are likely to be similar to those affecting open-coast sandy shores (see Section 2.3) and sea-cliff shores (see Section 2.8). However, there are several additional local or regional factors that may partly determine the response of slump-prone shores to sea-level rise. The factors likely to determine the response of slump-prone shores to sea-level rise include (but are not necessarily limited to):

- *Wave Climate*: The amount of wave energy received on a particular coast and the frequency and intensity of storms attacking a shoreline will strongly control the rate at which wave attack causes toe erosion at the base of the coastal slope to trigger slumping.

- *Tide Range*: Where tidal ranges are smaller, wave energy is concentrated on a narrower vertical range at the base of the coastal slope and is thus likely to cause more rapid erosion within that zone, leading to the triggering or slumps. Where tidal ranges are larger, wave attack will be dispersed over a greater vertical range, and may thus result in a slower overall rate of erosion and slumping (see also Sections 2.3 & 2.8: the same principle applies to erosion of open ocean sandy shores and sea cliffs).

- *Exposure*: Orientation (or aspect) and exposure of a slump-prone coastal slope to the most important prevailing storm wave approach directions for that part of the coast will affect its susceptibility to wave attack.

- *Shoreline Plan-form and Seabed Topography (bathymetry):* The topography of the sea bed and plan form of the shoreline affects wave refraction and propagation patterns. For example, wave refraction concentrates wave energy on protruding headlands, causing faster erosion and slumping there, whereas offshore islands and reefs may absorb and disperse wave energies, giving more protection to certain segments of a slump-prone shoreline. Again, the form and slope of the near-shore subtidal zone in front of a slump-prone shore will determine the degree to which wave energy is dissipated (or not) before waves strike the toe of the coastal slope.

- *Bedrock Surface Topography:* Where a slump-prone coastal slope comprises unconsolidated slope deposits (colluvium) over a relatively unweathered "solid" bedrock base, the form of that bedrock base can partly determine the susceptibility of the shore to slumping. For example, large protruding bedrock outcrops may "anchor" the slope deposits and reduce the potential for slumping.

- *Substrate Type and Coastal Slope Angle:* The propensity for slumping - whether on the coast or inland – may vary depending on the substrate type and slope angle. Thus, for example, old basaltic landslide deposits on a coastal scarp may slump at gentler slope angles than many other types of slump-prone substrates.

- *Precipitation Intensity & Frequency:* In addition to the removal of toe support from a coastal slope as a result of wave erosion, saturation of slump-prone substrates with water is a significant factor in triggering slumping. Thus, the susceptibility of a coastal slope to slumping may be partly dependant on the frequency and intensity of heavy rainfall events in particular coastal areas. If climate change results in more frequent intense rainfall events in some regions, vulnerable coastal slopes in such areas may become increasingly prone to slumping in the future.

Tasmanian Examples
Shores prone to slumping occur at a variety of locations around the Tasmanian coast, and in a number of cases are a significant problem for coastal developments since some slump-prone shores occur in densely populated coastal regions such as Hobart (Taroona), the Tamar estuary (Launceston), St Helens (Parnella) and along the north and northwest coast (Boat Harbour to Devonport region).

Substrates prone to slumping on the Tasmanian coast include basalt colluvium (old landslide deposits) and deeply weathered basalt bedrock in the Boat Harbour to Devonport region, semi-lithified clayey-gravelly Tertiary-age sediments (at Macquarie Harbour, Tamar estuary, St. Helens and Taroona), dolerite slope deposits and intensely fractured and weathered dolerite bedrock (Bruny Island and Tasman Peninsula), and intensely fractured and weathered Permian – age siltstone bedrock (Forestier Peninsula).

Vulnerability Mapping
Many Tasmanian shores prone to slumping and progressive ongoing erosional retreat even without renewed sea-level rise, and to accelerated slumping with renewed sea-level rise, have been indicatively mapped during this project (*tascsthz_v2gda* map shapefile, *Erosvuln* attribute code 20: See Sections 4.3.5, A2.3.3).

This indicative mapping was possible since information exists on the distribution of several key slump-prone shoreline types, and this information has been incorporated into the base Shoreline Geomorphic Types data set used for this vulnerability mapping (*tascoastgeo_v4gda* / *tascsthz_v2gda*). In particular, the distribution of semi-lithified Tertiary sediment substrates around the Tasmanian coasts is mapped to a reasonable level of confidence on available published geological mapping. Until recently, however, the distribution of basaltic slope deposits and deeply weathered basalts on the

Tasmanian coast has only been poorly mapped, as most such deposits were formerly depicted only as solid basalt bedrock on older geological maps. This lack of information was one reason why the first edition of this vulnerability mapping (Sharples 2004a) did not include a coastal slumping vulnerability assessment, since basaltic slump-prone shores were known to be present along the densely populated north coast but their distribution was inadequately known for the purposes of vulnerability mapping. In many cases these substrates are soil-covered and vegetated on the coastal slopes immediately above the High Water Mark, and hence were difficult to identify from the air-photo interpretations upon which much of the original version of the Shoreline Geomorphic Types map *tascoastgeo_v4gda* was based (Munro 1978, Sharples 2000).

However, Mineral Resources Tasmania has recently undertaken new field mapping of these basaltic substrates along the north coast, as part of a landslide hazard assessment project, and draft versions of this mapping (mapped and supplied by Clive Calver of Mineral Resources Tasmania) have been used to update the *tascoastgeo_v4gda / tascsthz_v2* geomorphic mapping.

The addition of this new mapping provided sufficient coverage of slump-prone shore types on the more densely-populated coasts of Tasmania as to make an indicative slump vulnerability assessment of Tasmania's coast worthwhile undertaking. However, there do remain several categories of slump-prone coastal substrates whose distribution remains poorly known, particularly dolerite colluvium and deeply weathered and intensely fractured dolerite bedrock. Much of these latter substrate types appear to form coastal slopes in mostly uninhabited coastal regions including parts of South Bruny Island and Tasman Peninsula, and hence are of lower priority for mapping from a coastal development management perspective. Nonetheless, it is hoped that future geological mapping will identify more of these coastal substrate types so as to allow the coverage and accuracy of the indicative coastal slump vulnerability mapping to be improved in future.

2.8 *Sea Cliff Rock Fall, Collapse and Retreat*

This vulnerability category refers to vertical sea cliffs in hard lithified bedrock which are exposed to storm wave action. Sea cliffs identified in the shoreline geomorphic types data set (*tascoastgeo_v4gda*, Sharples 2006) upon which this vulnerability assessment is based are nominally those higher than 5 metres (see Appendix 2[16]), and may be topped by tiers of higher cliffs, steeply sloping bluffs (which may have slump zones and colluvial slopes above the basal sea cliff) or flat to gently sloping ground.

Sea cliffs have been actively developing and receding landwards on many bedrock shores around the Tasmanian coast since the sea reached approximately its present level 6,500 years ago (Thom & Roy 1985), at the end of the last post-glacial marine transgression. Many present day sea cliffs are probably at least in part rejuvenated cliffs that formed during past interglacial climatic phases when sea level was within a few tens of metres of its present level, were partly degraded by terrestrial erosion when sea level dropped during the Last Glacial phase, and have subsequently been rejuvenated by renewed and ongoing wave attack following the last post-glacial marine transgression. Sea cliffs are formed where sufficiently steep coastal bedrock profiles are attacked at the base by storm waves, causing undercutting or over-steepening leading to slumping, collapse or rock fall from the steep profile above. These processes lead to progressive retreat of the cliff-line, which will continue irrespective of sea-level rise as long as the cliff base remains exposed to wave action. Most sea cliff erosion is initiated by storm waves, although subsequent collapse or slumping of the cliff profile may be partly triggered by terrestrial processes such as heavy rainfall saturating the over-

[16] Cliffs lower than a nominal 5 metre height may not be recorded as such in the dataset, but rather will be classified simply as "rocky shores" (see Appendix section A2.3.1).

Figure 15: Active retreat of a highly exposed sea cliff at High Yellow Bluff on the east coast of Forestier Peninsula, southern Tasmania, is causing active slumping of coastal colluvium (see also Section 2.7). The lower grey section of the cliff comprises clay-rich, highly weathered and fractured siltstones which are particularly susceptible to erosion. This sea cliff retreat is probably largely due to an ongoing process of shoreline adjustment to the post-glacial marine transgression that ended 6,500 years ago, however renewed sea-level rise can be expected to accelerate these processes.

steepened or undercut cliff mass. Vertical sea cliffs are more likely to develop where the steep eroding bedrock shore is relatively unweathered, in contrast to coastal slump zones (as described in Section 2.7 above) that are more likely to develop where coastal bedrock is intensely fractured and deeply weathered.

Sea cliffs may slope steeply into the sub-tidal zone, or may exhibit basal shore platforms or talus deposits. In some cases narrow intertidal sandy or cobble beaches may be present at the cliff base. In general, bolder cliffs form in locations more exposed to strong wave action from the open sea (Bird 2000, p. 51), however the degree of vertical cliff development also depends on other factors including the structure and fracturing of the bedrock, and its lithology. For example, steep exposed coastal profiles on tough, widely-fractured granites may show little actually-vertical cliff development (as at parts of "The Hazards" shoreline at Freycinet Peninsula), whereas softer and more intensely fractured Permian siltstones have formed high vertical and overhanging cliffs in exposed locations at Tasman Peninsula.

Sea cliff development is part of the general process of coastal landform re-adjustment that occurs each time the mean sea-level changes, and present day vertical sea cliffs in Tasmania have undoubtedly been, and remain, subject to ongoing marine erosion and cliff retreat throughout the last 6,500 years of the Holocene. Sea cliff recession rates have not been determined in Tasmania, however Sunamura (1992, in: Bird 2000, p. 73) has presented global average linear sea cliff recession rates during the Holocene ranging from 1mm/year on granite cliffs, to 1cm/year on shale cliffs, to 1 – 10m/year on unlithified glacial sediments. Average figures such as these may serve as useful indicators of potential cliff recession rates in the absence of any better local data.

As noted previously (see Section 2.3), bedrock sea cliff erosion is a progressive and irreversible process since, unlike sandy shores, material removed from rocky shores by wave erosion will not be returned to rebuild the shore. However cliff recession is also commonly episodic, since collapse or slumping of the cliff face in response to basal wave attack will result in accumulation of an apron of fallen blocks or slumped material (talus) at the cliff base, which protects the cliff base from further wave attack until the talus is removed by wave erosion.

Marine erosion and recession of vertical sea cliffs around Tasmania is undoubtedly ongoing, since in most cases their bases remain exposed to storm wave attack. Although rates of cliff recession (landwards retreat) are uncertain for most Tasmanian sea cliffs, average rates of about 1 metre horizontal recession per century on Permian siltstone cliffs might be anticipated based on global average cliff recession rates noted by Sunamura for shales (above). However, recession rates are likely to vary widely depending on a range of local variables (as listed below), and could be quite different for sandstone, dolerite, quartzite and other cliff bedrock types. Lee *et al.* (2001) describe approaches to predicting coastal cliff recession rates.

The effect of renewed sea-level rise is to focus wave attack a little higher up the cliff base than formerly, which may lead to an at-least temporary acceleration of cliff retreat rates as parts of the cliff base that were previously above the wave attack zone become exposed to direct wave action. Where a cliff base has been partly protected from wave attack by a shore platform or talus apron, deepening water over the near shore profile will lessen the protection afforded by shore platforms or talus aprons, and so cause an acceleration of cliff erosion as waves begin attacking the cliff base with more energy than previously.

If climate change results in more frequent intense storms or storms of greater intensity in the Tasmanian region, as is possible (Pittock 2003, p. 68), then this will also cause an acceleration of cliff retreat rates because it is storm waves that are responsible for most of the sea cliff erosion and retreat which occurs.

Fundamental Vulnerability Factors

The key factor identifying shorelines susceptible to sea cliff retreat of the sort described in this section is:

- The presence of a vertical cliff in hard lithified bedrock rising above the high water mark and exposed to storm wave action. A shore platform, talus apron or narrow intertidal sandy or cobble beach may or may not be present at the base of the cliff, however the cliff base (or talus apron at the cliff base) is reached by waves during large storms, at least.

Where a vertical cliff is present rising immediately above the high water mark, with or without a talus apron, this is an indication that cliff erosion and retreat is ongoing, and hence likely to continue or be accelerated with sea-level rise and climate change. Although exposure to storm wave action is a key factor in sea cliff development, the degree of exposure is not classified here as a fundamental vulnerability factor since sea cliffs may form to differing degrees in locations with differing degrees of exposure. Hence "exposure" is listed below as a locally variable vulnerability factor.

This vulnerability category refers to cliffs in hard lithified bedrock. Sea cliffs also occur in Tasmania in unlithified or semi-lithified coastal sediment deposits, including Tertiary-age sediments (e.g., at Macquarie Harbour). In many (but not all) cases such cliffs are lower than 5 metres or so, since unlithified sediments are less able to maintain a vertical face without slumping; however even where higher cliffs are present, the erosion and retreat of unlithified sediment shores (other than sandy shores) is dealt with as a separate vulnerability category in Section (2.6) above.

Regionally and Locally Variable Vulnerability Factors

Assessment of the *degree*, *pattern* and *rate* of erosional recession of sea cliffs in response to either a constant sea level or to sea-level rise, requires a more detailed site specific assessment and coastal behaviour modelling process that takes into account any local variables which may modify the rates and patterns of cliff retreat at any particular site. Some of the regionally and locally variable factors that must be integrated into a detailed coastal behaviour model of sea cliff retreat include the following (Bird 2000, p. 72):

- *Wave climate*: The amount of wave energy received on a particular coast and the frequency and intensity of storms attacking a cliff base will strongly control the rate at which sea cliff retreat occurs.

- *Tide Range*: Where tidal ranges are smaller, wave energy is concentrated on a narrower vertical range at the cliff base and is thus likely to cause more rapid erosion within that zone, leading to cliff collapse. Where tidal ranges are larger, wave attack will be dispersed over a greater vertical range, and may thus result in a slower overall rate of cliff retreat (see also Section 2.3: the same principle applies to erosion of open ocean sandy shores).

- *Exposure*: Orientation (or aspect) and exposure of a sea-cliff to the most important prevailing storm wave approach directions for that part of the coast will affect its susceptibility to wave attack. The boldest sea cliffs generally form in locations most exposed to storm wave attack from the open sea (Bird 2000, p. 51-52).

- *Bedrock Geology (including degree of weathering and fracturing)*: The lithology and structure (especially susceptibility to weathering and joint or fracture spacing and orientation) of the sea cliff affects resistance or susceptibility to wave erosion. Thus for example in Tasmania, tough, widely jointed granites may resist wave attack well, whereas relatively more weathered and fractured Permian siltstone cliffs are more prone to wave erosion and collapse or slumping. Triassic sandstone cliffs in Tasmania are particularly prone to salt – weathering, which probably predisposes them to relatively intense wave erosion. The response of dolerite bedrock to wave action may vary widely, since some coastal dolerites are tough and widely fractured, while others are weathered, intensely fractured and thus more susceptible to wave erosion.

- *Near-shore profile (bathymetry) and presence or absence of basal shore platform or collapse debris*: The form and slope of the near-shore subtidal zone in front of a cliff base will determine the degree to which wave energy is dissipated (or not) before waves strike the cliff base. Similarly, a well-developed basal shore platform or a basal apron of collapse debris may give a cliff base greater protection from wave attack, although one effect of sea-level rise will be to reduce the protection afforded by a shore platform as the water deepens over the platform allowing further wave penetration during storms. Where occasional cliff collapses dump an apron of collapse debris at the cliff base, cliff retreat may be episodic with the cliff base being protected by debris following a major collapse until such time as wave action removes the debris and the cliff base is again exposed to wave erosion.

- *Shoreline plan form and seabed topography (bathymetry):* The topography of the sea bed and plan form of the cliffed shoreline affects wave refraction and propagation patterns. For example, wave refraction concentrates wave energy on protruding headlands, causing faster cliff erosion there, whereas offshore islands and reefs may absorb and disperse wave energies, giving more protection to certain segments of a cliffed shoreline.

Tasmanian Examples

Based on the *tascoastgeo_v4gda* Shoreline Geomorphic Map of Tasmania (Sharples 2006), coastal cliffs (nominally higher than 5 metres) in well-lithified bedrock occur on 1,359 kilometres (21%) of Tasmania's 6,472 km of coastline (see also Table 1 & Section 4.3.6). Of this, 1216 km are on exposed open-ocean shores, which highlights the importance of exposure to high wave energies in forming this type of coast. Of this exposed sea-cliff shoreline length, 317 kilometres are classified in the *tascoastgeo_v4gda* dataset as "high cliffed coasts" having sea-cliffs typically higher than 50 metres (i.e. *Profile* attribute = "4"; see Section A2.3.1).

Indeed, vertical bedrock sea cliffs around the Tasmanian coast include some of Australia's highest vertical sea cliffs in dolerite at Cape Pillar (Tasman Peninsula), high vertical cliffs in Permian-age siltstone bedrock near Eaglehawk Neck (Tasman and Forestier Peninsula's; see Figure 15), granite sea cliffs at Freycinet Peninsula, and a range of others. Few vertical sea cliffs in Tasmania are known to present a major risk to infrastructure resulting from cliff retreat since relatively little infrastructure has been constructed close to the crests of large vertical sea cliffs in Tasmania. However, unstable cliffs may present a risk to people as a result of rock falls where recreational access to cliff tops and basal shore platforms is available.

Vulnerability Mapping

Indicative or "first pass" mapping (see Section 3.2) of hard-rock coastal cliffs vulnerable to instability and accelerated retreat around the Tasmanian coast has been undertaken during this project (*tascsthz_v2gda* map, attribute *Cliffvuln*; see Section 4.3.6). A comprehensive first pass assessment was possible since data encoded in the available coastal geomorphic mapping (*tascoastgeo_v4gda*, Sharples 2006) identifies most Tasmanian coastal cliffs with a high degree of confidence (these features were readily identifiable on the stereo air photos upon which much of the mapping was originally based).

2.9 *Other Coastal Vulnerabilities*

This report and the accompanying indicative vulnerability mapping does not constitute an exhaustive assessment of all known or likely coastal geomorphic vulnerabilities pertaining to Tasmanian coasts. Some of the vulnerabilities and shoreline types that have <u>not</u> been considered in this report and the accompanying maps include:

- *Coastal dune mobility* is a natural process, although it has sometimes been triggered or increased by artificial disturbances (see Figure 16). Dune mobility can impact on infrastructure (houses, roads) or other artificial and natural assets such as back-dune farmland or wetlands, by means such as undermining or sand inundation. If coastal dune mobility were to increase in some Tasmanian coastal areas, then some assets that were not previously considered vulnerable to the impacts of dune mobility could become exposed to that hazard in future.

  There is potential for coastal dune mobility in Tasmania to increase, at least in some areas, as a consequence of both sea-level rise and possibly also other aspects of climate change (see Lees 2006). It is likely that storm wave erosion of dune fronts is already a major trigger of foredune blowouts and increased dune sand mobility (for example, at Ocean Beach and Nye Bay in western Tasmania), as it probably has been episodically throughout the Holocene. Thus, increased erosion of dune fronts as a consequence of sea-level rise (see Section 2.3) may trigger increased mobility in coastal dunes. In addition, certain climatic changes can increase dune mobility in other ways (Young *et al.*1993, Lees 2006). Increased aridity (due to decreased effective precipitation) may cause some dune vegetation to die back and

Figure 16: This large mobile transgressive coastal dune is moving towards and threatening to engulf farmland south of Cape Portland (northeast Tasmania). Whilst dune mobility of this sort is in some cases likely to have been exacerbated by human disturbances such as cattle grazing, it is a natural phenomenon in many coastal regions. Dune mobility is not always as dramatic as this example, and may also involve smaller blowouts and gradual movement of partly vegetated dunes such as foredunes, however these forms of mobility may also create significant difficulties for coastal management. There is potential for dune mobility at all scales to be increased as a result of dune front erosion by waves and changes to dune vegetation cover resulting from climate change.

expose dune sands to wind erosion. Increased average wind speeds may result in increased mobilisation of any exposed dune sands, and this will be particularly effective where vegetation dieback and wave erosion is exposing increased areas of sand to wind erosion. If climatic changes of these sorts occur in some Tasmanian coastal areas, then the likelihood of increased dune mobility in response to sea-level rise will be magnified.

- *Coastal groundwater tables* are likely to rise with sea-level rise, and salty groundwater wedges may penetrate coastal aquifers further to landwards than previously. However salty groundwater penetration and water table levels also partly depend on the rate of fresh groundwater recharge. If climate change results in increased precipitation and groundwater recharge in Tasmania, at least in winter (CSIRO 2001) or in certain parts of the state, then this could result in a seawards movement of the salty groundwater wedge, at least on a seasonal basis. Conversely, a decrease in effective precipitation (at least in some areas), would have the reverse effect of moving the salty wedge further inland, and/or of lowering the water table level.

- *Predominantly cobble and boulder beaches.* It is likely that predominantly sandy beaches with a minor cobble berm will behave essentially like other sandy beaches in response to sea-level rise (see Sections 2.3 and 2.4). However, the response of dominantly cobble or boulder beaches to sea-level rise is less clear. This includes those backed by low-lying cobbly sediment plains as at Lillico Beach and elsewhere on the central - northern Tasmania coast, and other cobble/boulder beaches on Tasmania's western and southern coasts. It is possible that the presence of dominantly cobble or boulder beaches may partly "armour" shorelines against the erosional effects of sea-level rise. However, these still constitute beaches composed of a (coarse) sediment capable of being mobilised by storm waves. The writer's observations of some cobble beaches on the Tasmanian north coast indicates that these do to some extent respond to storms with an offshore movement of cobbles, followed by a later return of cobbles to the beach, in a fashion somewhat similar to the sandy beach cut-and-fill cycle. Similar behaviour has also been observed on western and southern Tasmanian cobble/boulder beaches (M. Pemberton, *pers. comm.*). The response of this type of Tasmanian shore to sea-level rise is poorly understood at present, and although some erosion of these beaches might be expected, the likely rate and degree of recession of cobble beaches compared to sandy beaches is unclear.

- *Tsunami hazards* have not been addressed in this mapping. Tsunami's are large catastrophic waves generated, not by climatic factors, but rather by rare catastrophic events including submarine tectonic movements, volcanic eruptions or meteorite impacts. Tsunamis cause brief but highly destructive inundation of coastal areas by energetic masses of water that may wash considerably further inland than most storm surges would do. Bryant *et al.* (1992) and Young & Bryant (1992) consider that tsunamis have impacted on southeast Australian shores a number of times in recent millennia, although their evidence for this has been questioned by Saintilan & Rogers (2005), Williams & Hall (2004), and others. Nonetheless there is clear potential for tsunamis to affect Tasmanian shorelines, with potential triggers including tectonic movements on the Macquarie Ridge transcurrent fault southeast of Tasmania. In the wake of the disastrous Indian Ocean tsunami of December 2004, there is now considerable interest in detecting evidence of past tsunamis on southeast Australian shores, and in modelling the potential impacts of future tsunamis. However such work is beyond the scope of this report, and is not addressed by the vulnerability mapping accompanying this report.

2.10 *Minimal Vulnerability Rocky Shores*

All shoreline types exhibit change over time, in response to wave action and other natural processes in the coastal environment. However some shorelines change much more slowly than others, and as a general rule hard lithified bedrock shores typically show the slowest rates of change in response to natural coastal processes (Thieler & Hammar-Klose 1999). Of these, the most rapidly changing bedrock shoreline types are intensely fractured and weathered bedrock shores (see Section 2.7) and exposed vertical sea cliffs in harder, less weathered bedrock (see Section 2.8). However where the rocky bedrock shores are relatively unweathered or fractured and are not mantled by unconsolidated talus or colluvial deposits (see Section 2.7), and where steep coastal profiles and coastal geomorphic processes have not produced relatively high (> 5 metres) vertical sea cliffs immediately above the high water mark, in such situations gently to moderately sloping hard bedrock shorelines are typically the most stable and most slowly changing shoreline types on Tasmanian coasts (see Figure 17). Hence, these are the least vulnerable shores from a coastal development perspective, and the least likely to exhibit significant or accelerated rates of change with climate change and sea-level rise within time frames relevant to coastal development planning (e.g., 50 to 100 years).

Nonetheless, all bedrock shores on Tasmanian coasts have probably undergone some greater or lesser degree of physical change since sea level reached roughly its present level in the mid-Holocene about

Figure 17: A moderately sloping hard rock shoreline, in this case at Kingston, southern Tasmania. Shorelines such as this are likely to exhibit little flooding or geomorphic change in response to sea-level rise over the next century or so, although significant shore platform erosion has occurred on some such shores over the 6,500 years since the end of the post-glacial marine transgression, when sea level attained roughly its present level (Thom & Roy 1985).

6,500 years ago. As with other non-sandy shorelines, the erosion of sloping bedrock shores in response to wave attack is an irreversible and progressive process that over a very long period of stable sea level would in theory tend ultimately towards a low equilibrium profile, although this is probably rarely if ever reached in a single sea-level still-stand (see also Section 2.8 above). The development of vertical sea cliffs on steeper bedrock shoreline profiles during mid- to late-Holocene times has been discussed in Section (2.8) above. However where coastal bedrock profiles are lower and/or wave exposure is less, with gently to moderately sloping bedrock surfaces rising from the waterline, cliff development has been limited and many hard bedrock shores have evidently changed only very slowly. Many of these shores have maintained a sloping profile that is probably largely inherited from those natural erosion processes that shaped their contours in a terrestrial (inland) environment during the last glacial climatic phase when sea level was well below the present level (Lambeck & Chappell 2001).

However, on some sloping bedrock shorelines, typically those most directly exposed to wave action, certain notable changes have occurred during the last 6,500 years while sea level has been at roughly its present level. Typically these changes have included the wave-excavation of flat to gently sloping rocky shore platforms in the intertidal zone, and in some cases the excavation of a low cliff or scarp (typically less than 5 metres high) at the back of the shore platforms. The presence of such features is indicative of the degree of marine erosion that can and has occurred on some hard sloping bedrock shores over a period of 6,000 years or so. In most cases this equates to a rate of erosion which is slow and unlikely to be a risk for coastal developments within typical planning periods of 50 to 100 years.

In the context of both present-day conditions and future climate change and sea-level rise, gently to moderately sloping hard bedrock shores – without significant colluvial or talus mantles and with or without intertidal rocky shore platforms and/or low (typically <5 metre) cliffs or scarps – are the least risky Tasmanian shoreline types from the perspective of coastal development because:

- rates of shoreline erosion, under current or further-rising sea levels, are likely to be minor within typical planning periods of 50 to 100 years;
- lack of significant colluvial mantles means there is minimal vulnerability to slumping on such shorelines (see also Section 2.7); and
- the sloping profile means that storm surges are unlikely to flood infrastructure placed relatively close to the shore, as the sloping profile means that infrastructure quite close to the shore (horizontally) can easily be placed several metres above sea level and thus out of the range of likely or predictable storm surge flooding within typical planning periods of 50 to 100 years (see also Section 2.2).

Fundamental Minimal – Vulnerability Factors

The key factors identifying those Tasmanian shorelines least vulnerable to coastal flooding and erosion hazards of the sorts described in this report are:

- gently to moderately sloping hard bedrock shores;
- without significant colluvial or talus mantles; and
- without vertical cliffs rising over roughly 5 metres, immediately above the high water mark.

Such shores may be with or without intertidal rocky shore platforms or low (typically <5 metre) cliffs or scarps.

Regionally and Locally Variable Vulnerability Factors

Whereas most shores of the sort described by the above "fundamental minimal vulnerability factors" are unlikely to exhibit significant erosion or storm surge flooding risks for coastal development and infrastructure over typical planning periods of 50 to 100 years, there may be some variability in their vulnerability to such hazards over longer time frames. Factors that may cause such variability include (but are not necessarily limited to):

- *Wave Climate*: As with other coastal hazards, more energetic wave climates (i.e., shores exposed to more energetic waves and more intense storms) are likely to result in more rapid erosion than elsewhere.
- *Tidal Range:* As with several other shoreline types described above, larger tidal ranges are likely to result in greater dispersal of storm wave energies over the vertical shoreline profile, resulting in the slowest rates of shoreline erosion and retreat (Thieler & Hammar-Klose 1999).
- *Exposure*: Those shores least exposed to the prevailing storm wave approach directions for their coastal region are likely to show the least erosion of all; with sea-level rise, more exposed shores may show some renewed shore platform excavation at higher levels sooner than more sheltered shores, albeit such erosion will still be very slow compared to other shoreline types.
- *Bedrock type*: Lithology and structure has a strong effect on bedrock shore erosion rates. Some sloping bedrock shores, such as widely-fractured granite shores, are likely to show much slower erosion than, say, intensely-fractured siltstone bedrock shores, or Triassic sandstone bedrock shores that are susceptible to salt-weathering.

- *Presence or absence of shore platforms and low cliffs*: The presence of an intertidal shore platform or low cliff just above high water mark, on an otherwise gently to moderately sloping bedrock coastal profile, is suggestive of a location on which geomorphic conditions (e.g., exposure) or litho-structure (rock type and fracturing or bedding structures) allow a higher rate of marine erosion of rocky shorelines than elsewhere. While the rate of erosion of such shorelines will still be slow compared to the other types of coastlines considered in this report, their possession of marine erosion features (cliffs, shore platforms) indicates that they are eroding faster than rocky shorelines which simply slope gradually and continuously into the sub-tidal zone. The latter can thus be considered the shoreline type least vulnerable to erosional change with sea-level rise, whereas the presence of shore platforms and low cliffs on otherwise moderately sloping bedrock shores may indicate a slightly higher (but still low) vulnerability to erosional change with sea-level rise.

- *Coastal profiles and plan-forms*: As is true for a variety of other coastal vulnerabilities described in this report, the rate and style of such erosion as does occur on these shores will vary depending on the ways in which coastal plan-forms and subtidal profiles concentrate or dissipate wave energies at certain points along a shoreline (see also Sections 2.2, 2.3 & 2.8). Again, the more gently sloping rocky shorelines will be proportionately more susceptible to storm surge flooding and storm wave run-up than more steeply sloping shores, albeit storm surge flooding vulnerabilities are likely to remain relatively limited unless extensive, nearly flat, rocky coastal slope profiles are present.

Tasmanian Examples

Moderately sloping hard bedrock shores occur commonly around the Tasmanian coast, with mapped occurrences in the *tascoastgeo_v4gda* and *tascsthz_v2gda* datasets accounting for at least 1259 km (19%) of the Tasmanian coast (including the Bass Strait islands; length calculated from 1:25,000 shoreline mapping: see Section 4.3.7). Due to the typically low level of coastal vulnerability associated with these shores, they provide some of the safest and least problematical locations for construction of coastal residences and other infrastructure. Indeed, for people wishing to build safely in locations having views over and easy access to sandy beaches, locations on rising rocky shores at the ends of beaches are probably the premium choice.

Vulnerability Mapping

Indicative or "first pass" mapping (see Section 3.2) of minimal vulnerability shorelines around Tasmania has been undertaken during this project (*tascsthz_v2gda* map shapefile, *Minvuln* attribute; see Section 4.3.7). Available coastal geomorphic mapping (*tascoastgeo_v4gda*, Sharples 2006) is sufficiently comprehensive and robust as to allow indicative mapping of shores having the fundamental minimal vulnerability factors (above) that characterise minimal vulnerability shores of the sort described above. In most cases, bedrock shorelines are easily identifiable on air photos, and this was done during the preparation of the shoreline geomorphic map used in this coastal vulnerability assessment (*tascoastgeo_v4gda*: Munro 1978, Sharples 2006). The presence or absence of significant sea cliffs is similarly readily evident on air photos, while comprehensive 1:25,000 scale topographic mapping of the Tasmanian coast provides a good indication of coasts with gently to moderately sloping profiles. It should be noted, however, that mapping of vegetated talus or colluvium-mantled shores is incomplete (albeit improving) for Tasmania (see Section 2.7), hence it is possible that some shores mapped as "Minimal Vulnerability" in this assessment may be shown by site-specific field inspections to be slump-prone shores not readily identified as such from air photos.

3.0 COASTAL VULNERABILITY ASSESSMENT METHODOLOGIES

3.1 *Introduction*

Identification and assessment of shorelines susceptible to increased rates of geomorphic changes ("impacts") related to climate change and sea-level rise can occur at three levels:

1. *Indicative or "first pass" identification* of shorelines potentially vulnerable to some (unspecified) degree of significant impact, based on identification of shores exhibiting the *fundamental vulnerability factors* for a particular coastal hazard (as outlined in Section 2.0), where these can be rapidly determined at a regional or state-wide level (the likely *degree* of impact at any site remains undefined).

2. *Regional and site-specific assessment and modelling* of the relative degrees, patterns and rates of change or impact on specific coastal segments identified as potentially vulnerable in an indicative assessment. This level of assessment is based on identification, mapping or measurement and assessment of a wide variety of *regionally or locally variable vulnerability factors* which may determine and modify the way in which any particular "indicatively vulnerable" shore responds to sea-level rise and climate change.

This level of assessment can be sub-divided into two sub-levels, namely:

1. *Regional or "second pass" indicative assessment*, consisting of a refinement of an indicative assessment using information on regionally-variable vulnerability factors (such as wave energy) for which comprehensive mapped data is readily available at regional or state-wide levels. This quickly gives a refined but still incomplete vulnerability assessment for particular shores, which begins to provide some differentiation of relative degrees of vulnerability between sites, but is still inadequate for detailed coastal behaviour modelling;

and:

2. *Site-specific assessment and modelling* of physical coastal behaviour, based on detailed field mapping and assessment of all relevant regionally and locally variable climatic, oceanographic, geological, geomorphic, topographic and hydrologic vulnerability factors affecting response to hazards at a particular coastal site. This is a detailed and time consuming level of assessment, but one which can yield the best available coastal behaviour models and predictions of the degree, pattern and rates of coastal change or hazard impact at particular sites.

3. *Ongoing (long term) measurement and monitoring of coastal behaviour* at specific sites to measure actual coastal changes and to test and refine predictive coastal behaviour models for those particular shores. This involves repeated physical, quantitative measurement and monitoring of the profiles, topography, geomorphic processes and flooding levels of particular shorelines over periods of time sufficiently long to discern long-term trends and patterns of shoreline change. Such monitoring can allow the predicted (or "modelled") behaviour of a shoreline to be compared with its actual behaviour over time, so as to test and refine coastal behaviour models, and may also provide some real indication of ongoing and future *rates* of physical change of the shoreline in response to climate change and sea-level rise.

These three levels of assessment are best regarded not as alternative methods of vulnerability assessment, but rather as three sequential and complementary components of an ideal integrated coastal vulnerability assessment strategy. Whereas site-specific modelling of shoreline behaviour, and monitoring to test and refine such modelling, is ultimately essential to provide reasonably confident assessments of the degrees, patterns and rates of coastal change likely to occur on particular shorelines due to sea-level rise, these levels of assessment are time consuming and may be relatively expensive to conduct. Furthermore, because of the number and variability of the locally-variable vulnerability factors that may modify shoreline behaviour, no two shores can be expected to respond to sea-level rise in identical ways, hence each shore must be specifically assessed and monitored in order to arrive at any detailed assessment of its likely behaviour. Site-specific modelling and monitoring is only just commencing in Tasmania, and it is likely to be some years before reasonably confident assessments of these sorts are available for any shores.

However Tasmanian coastlines are under immediate and mounting pressure for coastal developments of various sorts, and planners and Local Governments are under pressure to approve developments in coastal locations that may in some cases be susceptible to sea-level rise and climate change impacts. There is an immediate need to give decision-makers some form of guidance as to which coastal locations may be potentially susceptible to such impacts.

The three-level (or "three stage") assessment strategy outlined here provides a means of providing a quick initial "indicative" identification of shorelines potentially susceptible to *some* degree of impact from sea-level rise and climate change. This provides a precautionary basis for decision-makers to proceed on, while also providing a basis for selecting high-priority shores for more detailed and time consuming site-specific assessments and monitoring, leading over time to progressively more rigorous and confident assessments of the actual degrees, patterns and rates of change to be expected on those particular shores.

This project provides an indicative first-pass identification of Tasmanian shorelines potentially vulnerable to a range of coastal hazards related to sea-level rise and climate change, and also provides an indicative identification of a class of shorelines likely to be only minimally vulnerable to significant physical impacts over the next century or so (see Section 4.3). Several of the regionally and locally variable factors required for regional or site-specific assessments of relative levels of vulnerability have also been partially mapped (see Appendix 3), however this information does not constitute a complete site-specific vulnerability assessment for any Tasmanian shorelines.

Each of these three levels of assessment is considered further below:

3.2 *Indicative ("First Pass") Assessment*

In essence, an indicative or "first pass" assessment gives a simple "potentially vulnerable" or "not potentially vulnerable" assessment based on first-order criteria ("fundamental vulnerability factors"), but provides no ranking of different degrees of vulnerability between the various shores identified as "potentially vulnerable".

An indicative assessment can be conducted on a State wide basis to identify areas vulnerable to *some* degree of potentially significant shoreline erosion, flooding or other impact. An indicative assessment proceeds by identifying shores having certain fundamental characteristics – or *fundamental vulnerability factors* – predisposing a shoreline to a particular hazard.

"Fundamental vulnerability factors" in this context are those basic geomorphic characteristics that determine whether a shoreline will be susceptible or vulnerable *at all* to a particular hazard. Various additional vulnerability factors may modify the degree of susceptibility of a shoreline, but the fundamental vulnerability factors determine whether it has any degree of susceptibility to a particular hazard in the first place. For example, susceptibility to storm surge flooding fundamentally depends on the existence of low-lying coastal flats immediately inland of the high water mark, whose surface lies within the range of previous or predictable storm surge levels for that coast. Other factors such as shoreline exposure to storm surge directions, subtidal topography and coastal plan form may modify the degree of flooding which occurs, but low-lying coastal topography is the *fundamental vulnerability factor* for this particular hazard. Section (2.0) above outlines the fundamental vulnerability factors for each of a range of potential coastal hazards associated with climate change and sea-level rise.

The key advantage of an indicative coastal vulnerability assessment is that:

- it can rapidly provide a precautionary basis for planners and responsible decision-makers to proceed to assess coastal development proposals which they are under pressure to make decisions on.

However, the key prerequisite for undertaking an indicative coastal vulnerability assessment is:

- the existence of comprehensive geomorphic maps or databases, at relatively detailed map scales, which contain appropriate information on the coastal distribution of the fundamental vulnerability factors for each category of coastal hazard.

Tasmania possesses comprehensive State wide coastal geomorphic mapping of this sort containing appropriate data on the fundamental vulnerability factors for a number of key coastal hazards; this map data (*tascoastgeo_v4gda*) is described in Section (4.2.1) and Appendix 2.

Broad-scale assessments of coastal vulnerabilities related to sea-level rise have been undertaken in the USA (Thieler 2000, Thieler & Hammar-Klose 1999). The latter assessments are essentially indicative assessments in the sense defined here, involving no site-specific assessments, however a number of regionally-variable oceanographic factors were also taken into account in addition to the fundamental (geomorphic) vulnerability factors. Thus, the US assessments may be better classified as "second pass" indicative assessments in the sense used in Section (3.3.1) below. Similar coastal vulnerability assessments have also been undertaken for the Canadian coasts (Shaw *et al.* 1998).

The present report describes a comprehensive indicative (first pass) coastal vulnerability assessment for Tasmania which is to the author's knowledge the first such assessment undertaken for any coast of comparable length.

3.3 *Regional and Site-Specific Assessment and Modelling*

Whilst numerous shorelines may possess the fundamental geomorphic characteristics (or *fundamental vulnerability factors*) making them potentially susceptible to a particular coastal hazard in some unspecified degree, the actual degree to which that hazard will impact on particular shores may vary widely depending on a range of additional *regionally and locally variable vulnerability factors* (environmental characteristics) such as those noted in Section (2.0). A regional or site specific vulnerability assessment is one which takes into account those additional regional and local variables in order to give some assessment of the likely relative degrees, patterns and rates of change or impact at different specific sites.

This level of assessment can be sub-divided into two sub-levels, namely:

3.3.1 Regional or "Second Pass" Indicative Assessment

A "second pass" indicative assessment is here considered to be one which gives an initial ranking of higher and lower vulnerability shores (which can be expressed by a numerical vulnerability ranking), based on considering selected second order criteria ("regionally variable vulnerability factors") in addition to the fundamental vulnerability factors. However it is possible for such a ranking to be deceptive, because the second-order criteria chosen to rank vulnerability of different shores may not necessarily be the most important variables in all cases.

This level of assessment consists of a refinement of an indicative ("first pass") assessment using information on additional relevant regionally-variable vulnerability factors or environmental characteristics (such as tidal range or wave energy zone) for which comprehensive mapped data is readily available at regional or State wide levels. This quickly gives a somewhat refined regional-scale assessment of coastal vulnerability which begins to allow some differentiation or ranking of relative degrees of vulnerability between particular sites.

However, there is a need to exercise caution with the interpretation of a regional indicative vulnerability assessments of this sort, because it may not be clear that the regionally variable vulnerability factors for which regional-scale data are available, and that can be integrated into such a regional-scale assessment, are in fact always as important as other locally-variable vulnerability factors (e.g., local bedrock topography) that can only be determined on the basis of detailed site-specific assessments (below). That is, once an assessment of coastal vulnerability proceeds beyond the basic "first pass" stage of considering only the *fundamental vulnerability factors*, then there is a possibility that consideration of some but not all relevant *regionally and locally variable vulnerability factors* will produce an unreliable assessment of the relative degrees of vulnerability at a range of particular coastal locations.

An approach to coastal vulnerability assessment that uses a "Coastal Vulnerability Index" (CVI) has been adopted in a number of countries (e.g., South Africa: Hughes & Brundrit 1992; USA: Thieler 2000, Thieler & Hammar-Klose 1999). The CVI approach (Gornitz & Kanciruk 1989) assesses coastal vulnerability to sea-level rise at a regional level, over long stretches of coastline, by identifying fundamental vulnerability factors (coastal geomorphic and geological types, including coastal relief), and integrating these with a selection of regionally variable vulnerability factors (tidal range, wave climate, historical rates of horizontal shoreline movement, and any vertical land movement). As such, the Coastal Vulnerability Index (CVI) approach to coastal vulnerability assessment is a good example of a "second pass" indicative assessment in the sense used in this report. The CVI method remains indicative only, however, since it is conducted at a regional level and does not consider a range of local variables that can significantly modify the vulnerability of particular sites.

In Tasmania, Leaver (2005) has built upon the first edition of the present "first-pass" Tasmanian coastal vulnerability assessment (Sharples 2004a) by developing a Coastal Vulnerability Index for Tasmanian coasts and applying this to a pilot study area in southern Tasmania. This constitutes the development of a Second Pass Vulnerability Assessment methodology for Tasmanian Coasts, and is intended to be developed further in the future.

3.3.2 Site-Specific Assessment and Modelling

A site-specific vulnerability assessment ideally takes into account all relevant regionally and locally variable vulnerability factors to yield a model of how that particular coastal site is likely to behave in response to sea-level rise (and/or other coastal hazards). Such an assessment is not expressed as a vulnerability ranking or index, but rather as a physical description of the likely types, rates and magnitudes of impacts at that site.

A site-specific assessment of coastal vulnerability is the most reliable means of predicting the likely degree, pattern and rates at which coastal hazards may impact on a particular coastal stretch or area that has been identified as potentially vulnerable by an indicative first pass assessment. However this level of assessment requires a considerable investment of time and money. Site-specific assessment involves detailed field mapping and assessment of all the identifiable *regionally and locally variable vulnerability factors* determining the likely response of a particular coastal area to sea-level rise and climate change, and the integration of these data to produce a coastal behaviour model for the particular area. Such a model is essentially a detailed hypothesis as to the degree, patterns and rates of change that are likely to occur in that particular coastal area in response to both contemporary processes and ongoing sea-level rise and climate change.

This level of assessment will involve site-specific studies of *regionally and locally variable vulnerability factors* including but not necessarily limited to the following:

- Analysis of any available tide gauge, wave and weather records relevant to the site, to determine historically prevailing and contemporary wave climates, tidal ranges, storm surge levels, storm frequencies, intensities and approach directions, and other relevant oceanographic and climatic conditions of the site;

- Consideration of projected future sea-level changes, climatic variations and possible changes to wave climate at the site;

- High resolution topographic mapping and profile measurements, including beach, dune and backshore elevations and profiles;

- Detailed geological mapping of bedrock types, degree of fracturing and weathering and bedrock surface topography. Mapping of the type, thickness and distribution of unconsolidated sediments overlying bedrock at the site. Where relevant, drilling or augering to determine unconsolidated sediment thicknesses on or behind the shoreline may be necessary;

- Bathymetric (topographic) mapping of the form of the offshore sed bed adjacent to the coastal site in question;

- Studies of offshore sediment movements including the effects of littoral drift, tidal currents and storm waves affecting the shore;

- Consideration of the likely effects of the local shoreline plan form, profile and seabed topography on storm wave refraction, wave set-up and wave run-up;

- Consideration of local sediment sources and sinks, allowing determination of sediment budgets where relevant;

- Consideration of the effects of any artificial disturbances of coastal geomorphic or oceanographic processes at the site; and

- Consideration of historical and contemporary data on shoreline movement (erosion/accretion) to date.

The determination and integration of all of this information and more in the light of contemporary theoretical understanding of the type of coastal geomorphic process system concerned can allow a detailed coastal behaviour model to be developed for the particular coastal location. Such a model is essentially a detailed hypothesis as to how coastal processes function at the site under prevailing conditions, and how they are likely to be modified by ongoing climate change and sea-level rise. This approach can provide the most reliable assessment possible of the relative degrees, patterns and rates of coastal changes likely to occur at the particular site under existing and future conditions.

However, it must be emphasised that even a detailed site-specific assessment such as this still only produces a coastal behaviour model that is essentially the best available hypothesis and prediction as to the likely geomorphic behaviour of the site. Such a hypothesis still requires testing and confirmation, and the only means to achieve this is by monitoring of actual coastal behaviour and change at the site over time, and comparing actual behaviour with the predictions of the coastal behaviour model (see further below).

A number of assessments that could be described as site-specific modelling of sea-level rise impacts have been undertaken on mainland Australia. These include an assessment of potential erosion impacts on Perth beaches, which considered factors such as sediment transport and coastal bedrock topography (Jones & Hayne 2003), GIS-based modelling of shoreline recession potential on beaches and coastal re-entrants in the Sydney region (Hennecke 2000, Hennecke & Cowell 2000), an assessment of coastal erosion potential at Byron Bay, NSW (Andres *et al.* 1999), and the application of the Shoreface Translation Model to a variety of Australian beaches (Cowell *et al.* 1995, 1995a).

No assessments of this sort have yet been completed in Tasmania, and the commencement of site-specific coastal vulnerability assessments of high-priority coastal areas identified as potentially vulnerable by the indicative assessment described in this report, remains an urgent need.

3.4 *Ongoing Monitoring and Refinement of Models*

Modelling future coastal behaviour, as described above, is subject to uncertainties – such models are essentially only hypotheses. Whilst a detailed coastal behaviour model – taking into account all relevant *regionally and locally variable vulnerability factors* – is necessary in order to be able to predict coastal responses to climate change and sea-level rise at particular sites with reasonable confidence, in order to confirm and refine such predictions it will be necessary to actually measure and monitor coastal behaviour at those sites over a period of time. In this way, the actual monitoring data can be used to test and progressively refine the coastal behaviour models that have been developed for each site through a site-specific assessment process of the sort described above.

A key issue for those directly responsible for managing coastal developments and infrastructure, such as Local Councils and planners, is the *rate* at which coastal changes will occur in response to climate change and sea-level rise. It will only be possible to have some confidence about predicting future rates of change when we have some monitoring data on actual shoreline changes with which to refine coastal behaviour models for those shores.

At a basic level, shoreline monitoring can involve regularly repeated measurements of shoreline profiles – preferably extending well into the backshore zone and as far into the sub-tidal zone as practical – which are tied into a fixed datum point. Such profiles need to be measured at intervals along a shoreline in order to obtain information on three-dimensional coastal changes. For example, three profiles (in the centre and towards the ends of a beach) would be the minimum essential to monitor both onshore-offshore sediment movements and alongshore movements, as well as determining the three-dimensional pattern of shoreline retreat where this is occurring.

At a more detailed and expensive level, analysis of high resolution ortho-rectified air photos taken at regular intervals, high resolution three-dimensional topographic mapping using differential kinematic

GPS (e.g., Hennecke & Greve 2003) or airborne laser mapping technologies (e.g., Sinclair *et al.* 2003) provide powerful methods of repeatedly mapping both onshore and offshore coastal topography at regular intervals so as to measure physical changes over time. In addition to monitoring changes in the topography or form of a coastal site over time, a comprehensive monitoring process would also endeavour to regularly measure other relevant geomorphic properties of the coastal system, such as changing sand grainsize distributions in various parts of the onshore and offshore environment, so as to assess changes in sand budgets and transport over time.

Long term beach profile monitoring has only been undertaken on two Australian beaches to date, namely Moruya and Narrabeen Beaches in NSW (Thom & Hall 1991, Short *et al.* 2000), however with increasing recognition of coastal hazards generally, and the likely impact of sea-level rise specifically, beach monitoring programs are now beginning to be implemented on a variety of Australian coasts.

No recorded beach monitoring data are available for Tasmanian shorelines, and to date little funding has been forthcoming to support such work. Some high-resolution beach monitoring using differential kinematic GPS has recently commenced at a few Tasmanian beaches, such as Raspin's Beach (Hennecke & Greve 2003). This work is however limited by a lack of available funding. The most extensive beach monitoring program currently under development in Tasmania is an ACE-CRC[17] and University-driven project called TASMARC (Hennecke *et al.* 2004, http://www.tasmarc.info), which is endeavouring to enlist community groups, such as Coastcare groups, to undertake simple regular profile measurements on local beaches using basic traditional surveying equipment (staffs, levels and tape measures).

However, whilst it is hoped that the low-budget and largely voluntary TASMARC project will yield valuable data on future shoreline changes in Tasmania, this does not eliminate the desirability of undertaking more detailed high resolution monitoring of high priority beaches. In particular, Tasmania possesses a mix of relatively disturbed shorelines (e.g., in south-east and northern Tasmania), as well as a long stretch of almost entirely undisturbed rocky and sandy shorelines on the south-west Tasmanian coast (Sharples 2003). A detailed monitoring project involving measuring changes on a range of "benchmark" undisturbed south-western beaches, as well as on a range of beaches in more settled and disturbed coastal areas of Tasmania, could yield valuable data on the ongoing rates and patterns of coastal change in Tasmania in response to sea-level rise and climate change. Such a project would allow comparison and improved understanding of both the "pure" impacts of sea-level rise unmodified by anthropogenic disturbances additional to sea-level rise (on undisturbed south-west beaches), and of the way in which these basic impacts are modified by additional anthropogenic disturbances in the more settled coastal areas where coastal changes are more likely to constitute risks to human infrastructure and assets.

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4.0 COASTAL VULNERABILITY ZONES IN TASMANIA

4.1 *Introduction*

Indicative ("first pass") coastal vulnerability mapping has been prepared for the whole of Tasmania (including Bass Strait islands and other major islands, but excluding Macquarie Island), for the following key vulnerabilities related to climate change and sea-level rise:

- coastal areas vulnerable to storm surge flooding (see Sections 2.2 & 4.3.2)
- open sandy coasts vulnerable to erosion (see Sections 2.3 & 4.3.3)
- sandy shores within coastal re-entrants vulnerable to erosion (see Sections 2.4 & 4.3.3)
- muddy (fine sediment) estuarine and deltaic shores prone to change with sea-level rise (see Sections 2.5 & 4.3.4)
- soft bedrock or colluvial shores vulnerable to progressive erosion and / or slumping (see Sections 2.6, 2.7 & 4.3.5)
- hard-rock coastal cliffs potentially vulnerable to rock falls, collapse, slumping and retreat (see Sections 2.8 & 4.3.6)

In addition, an indicative map of the following type of minimal vulnerability shorelines has been prepared:

- minimal vulnerability moderately sloping hard bedrock shores (see Sections 2.10 & 4.3.7)

Section 4.3 below describes the basis and rationales used to prepare indicative mapping of these key vulnerabilities. Indicative mapping of these types of shorelines has been undertaken for this project because they are key vulnerabilities which affect significant stretches of coastline in Tasmania, and because adequate (comprehensive and robust) mapped data on the fundamental vulnerability factors for the identification of these shoreline types is available (see Section 2.0).

In addition, mapping of certain regionally variable vulnerability factors, which can be used to provide an indicative "second pass" assessment of sandy coast erosion and storm surge vulnerability zones (as described in Section 3.3.1 above), has been partially prepared and is described in Appendix 3. However, further data collection will be required before "second pass" assessments of coastal vulnerability using these data can be undertaken for the whole Tasmanian coast.

4.2 *Base Data Used*

In addition to minor use of topographic contour maps, the two primary mapped data sources that have been used to prepare the indicative coastal vulnerability maps for Tasmania, as described in Section (4.3) below, are the 1:25,000 scale digital Tasmanian Shoreline Geomorphic Types Map (*tascoastgeo_v4gda*, Sharples 2006), and the 25 metre Digital Elevation Model (DEM) of Tasmania (2nd Edition, 2004). These data sets and their limitations are briefly described below:

4.2.1 Tasmanian Shoreline Geomorphic Types Map

The digital Tasmanian Shoreline Geomorphic Types Map (*tascoastgeo_v4gda*, Sharples 2006) is a descriptive geomorphic line map of Tasmanian coastal landform, bedrock and sediment types, which is licensed by the Tasmanian Department of Primary Industries & Water (DPIW). The map was supplied for this project by DPIW, and has been used to indicatively identify shoreline vulnerability zones, and minimal vulnerability shorelines, as described in Sections (4.3.3) to (4.3.8) below.

The current version of the Tasmanian Shoreline Geomorphic Types map is an updated version of an earlier digital map (*coastgeo_v1*) that was created in 2000 for the Australian Maritime Safety Authority's (AMSA) Oil Spill Response Atlas (OSRA), and for the Australian Coastal Atlas project (Sharples 2000). That original mapping project was instigated by Richard Mount (formerly of DPIW).

The original map was nominally digitised at 1:25,000 scale, and consists of a line map of the Tasmanian coast (nominally representing the Mean High Water Mark), which was manually divided into over 12,000 geomorphically distinctive individual segments, each of which was attributed with a range of descriptive information codes describing the coastal landforms and geology of the segment. These attributes provide a simple classification of coastal landforms by form and fabric, rather than primarily by genesis. The attributes are fully detailed in Appendix 2 of this report. Unfortunately, the digital line map used to generate the original Shoreline Geomorphic Types map did not include some important coastal re-entrants, such as Henderson Lagoon near Scamander (Figure 32) which were thus not included in the first edition of this indicative coastal vulnerability assessment (Sharples 2004a). Some of these coastal re-entrants (including Henderson Lagoon) have now been added to the shoreline geomorphic line map (*tascoastgeo_v4gda*), and form part of the second edition vulnerability assessment encoded in *tascsthz_v2gda*. However there still remain a number of further coastal re-entrants to be added to the base geomorphic mapping. This limitation in the base data set should be addressed in future by extending the Shoreline Geomorphic Types map to include all coastal re-entrants.

Data used to attribute the Tasmanian Shoreline Geomorphic Types map was obtained from a variety of sources, most notably including a set of original paper maps at 1:50,000 scale recording a geomorphic airphoto interpretation of the entire Tasmanian coastline undertaken by Revel Munro (geologist) in 1978 (Munro 1978). This earlier mapping was supplemented by additional airphoto interpretation by C. Sharples, comprehensive information from the most recent available 1:25,000 topographic mapping of the entire coast, the most recent available geological mapping, and information from a range of oblique coastal photographs and published geomorphic descriptions of certain parts of the Tasmanian coast. Unfortunately only limited ground-truthing of the map could be undertaken, and this remains the most important limitation on the accuracy of the Geomorphic Types map. An attribute is included in the data set which indicates whether or not a particular coastal segment has been ground truthed by field inspections (see Appendix 2).

The significance of the limited ground truthing varies depending on the type of information one wishes to extract from the map. For example, sandy shorelines are very easily identifiable on air photos, hence the mapping of sandy shorelines used to prepare an indicative assessment of sandy shore erosion vulnerability can be considered robust and accurate except for a few locations where sandy shores are extremely narrow. Sea cliffs and most rocky shorelines and shore platforms are also easily identified on air photos and their mapping can also be considered to have a high level of confidence. On the other hand, some shoreline types such as vegetated coastal colluvium shores (landslide debris) can be difficult to identify on air photos. Where such colluvial slopes have been recently active, they are easily identifiable on air photos; however older coastal colluvial slopes are often well vegetated and difficult to differentiate from solid bedrock slopes with a soil cover, even though they may still be at risk of future slumping due to sea-level rise (see Section 2.7). Recent upgrades to coastal colluvium mapping in the *tascoastgeo_v4gda* mapping are largely based on recent field mapping by Mineral Resources Tasmania, and the coverage of such mapping will only improve in future as further field mapping of this shoreline type is undertaken (see Section 2.7).

4.2.2 The 25 metre Digital Elevation Model of Tasmania

The 25m DEM of Tasmania is the most detailed digital topographic data set that is available for the whole of Tasmania in a single unified format. The DEM is a GIS grid data set consisting of 25 metre cells, each of which is attributed with the elevation in metres of its centre point above the Australian Height Datum as defined for Tasmania (see Section 1.6). The 25m DEM (2nd Edition 2004) was supplied for this project by DPIW, and was used to create the indicative storm surge flood vulnerability mapping created in this project (see Section 4.3.2).

The key issue for using the 25m DEM in this fashion is the resolution of vertical land surface elevation differences that it provides. The vertical spatial accuracy of the DEM varies considerably for different parts of Tasmania, since different data sources were used to construct the DEM in different areas of the State. The basic data source for the map was the 1:25,000 scale 10 metre LIST contour mapping which covers the whole of Tasmania. This has been supplemented in some areas by spot height measurements at varying spacings. However, the most accurate parts of the DEM are those areas where 1:5,000 topographic ortho-photo mapping is available and has been used to construct the DEM. These maps provide 5 metre contours and are available for a large part of the south-eastern Tasmania coastal region from Dover through Hobart to Cremorne area, and along a large stretch of the northern Tasmanian and Tamar coast.

The elevations of each grid cell have been determined by a non-linear interpolation between available 10m LIST contours, spot heights and 5m contours in areas of 1:5,000 mapping. Since coastal areas prone to flooding all lie on low-gradient coastal areas well below the 10m contour, interpolation of heights between AHD (0m) and the 10m LIST contours can be expected to yield a vertical height accuracy of no better than 2 metres in areas where the 10m contours were the only available data source (John Corbett[18], *pers. comm.*). However, better vertical accuracy can be expected in those areas where spot heights and/or the 1:5,000 ortho-mapping has been used to construct the DEM. Fortunately, many of the areas of significant coastal infrastructure development in Tasmania, where vulnerability to coastal flooding is a more critical problem than elsewhere, do in fact have 1:5,000 ortho-mapping which was used, hence the indicative flood vulnerability mapping provided with this report can be expected to be relatively more accurate for those areas.

In all areas, however, the grid cell size of 25 metres means that the horizontal resolution of DEM-derived mapping is limited to that 25m resolution.

Although the vertical accuracy of the 25m DEM is variable across Tasmania, and in some areas is quite poor considering that flood vulnerability assessment involves identifying vulnerable areas within regions of low profile coastal flats varying in elevation by less than 1 to 2 metres, it nonetheless constitutes the most accurate topographic data set currently available on a State wide basis, and thus provides the best indicative flood vulnerability zoning that can be achieved at the present time on a State wide basis. Identification of flood vulnerability zones at a more accurate level of spatial resolution will require the use of more detailed site specific topographic surveys where these exist, or the undertaking of such surveys.

A further source of inaccuracies in the 25m DEM is the existence of topographic errors in the data. An example of such an error was found at Mersey Bluff (Devonport), which the DEM indicated to be vulnerable to present-day storm surge flooding. However the bluff is a dolerite bedrock bluff rising well above this height. The flood vulnerability maps have been corrected manually for this known error (Figure 40). No other errors of similar scale in the flood vulnerability maps have been identified or corrected to date. Such errors are notified to DPIW as part of the ongoing improvement of their

[18] Consultant GIS specialist.

core land information data, hence over time it is expected that most errors of this magnitude will be eliminated from the data.

In essence, the indicative flood vulnerability areas identified in the maps accompanying this report, which are based on the 25m DEM, should be considered *only* as an indicative flagging of potentially flood-prone areas. Where an area is flagged by these maps as a potential flood vulnerability zone, this is intended to serve as a precautionary warning that more detailed topographic surveys and flood vulnerability assessments should be undertaken if new infrastructure developments or other relevant undertakings are planned for the indicated area.

4.3 *Indicative ("First Pass") Mapping of Potential Coastal Vulnerability Zones*

4.3.1 Introduction

This section describes Indicative, or "First Pass", mapping (as defined in Section 3.2) of several coastal vulnerability categories (as listed in Section 4.1), based on identification of coasts exhibiting the *Fundamental Vulnerability Factors* for each hazard, but without attempting to rank each category of shorelines into areas of greater or lesser vulnerability by integrating *Regionally and Locally Variable Vulnerability Factors* such as wave energy, exposure, sediment budget, or other site-specific variables.

4.3.2 Coasts with Significant Storm Surge Flooding Vulnerability

Coastal storm surge flooding hazards are described in Section (2.2). Any shore will experience some local rise in water levels during storm surges which might affect infrastructure placed very close to the High Water Mark (HWM). However shorelines classified as having a storm surge flooding vulnerability are those where there is potential for flooding during storm surges of significant areas to landwards of the High Water Mark, that are normally dry. This hazard will increase with sea-level rise, and could potentially also increase if the return periods of large-magnitude storm surge events decrease in the future (see Section 2.2).

The *Fundamental Vulnerability Factor* (geomorphic characteristic) pre-disposing a coastal area to storm surge flooding (Section 2.2) is:

- The presence of low-lying, low-profile coastal flats immediately backing the mean HWM.

For the purposes of the indicative assessment conducted during this project, coasts susceptible to storm surge flooding are taken to be those with significant low-lying backshore areas whose land surfaces lie within the height range of extreme storm surge events recorded by tide gauges for the region (or within a range interpolated between the nearest available tide gauge records), or which are likely to do so as a result of projected sea-level rise over the next century. It is conservatively assumed that sea-level rise will simply raise the level of potential storm surge floods by a height equivalent to the rise in sea level only. Whilst it is also possible that larger storms may occur more frequently in the future as a result of climate change, there is a lack of evidence as to whether or not this is occurring in mid-latitude Australian coastal regions.

It should be noted that the indicative flood vulnerability assessment described here does not take account of wave run-up (see Section 2.2), which is partly dependant on local variables that could only be assessed in the course of a site-specific flood vulnerability assessment (see Section 3.3.2).

Indicative Identification of Coastal Areas with Potential Storm Surge Flooding Vulnerability
The following procedure has been used to prepare digital polygon maps providing an indicative identification of Tasmanian coastal areas potentially vulnerable to storm surge flooding under contemporary (2004) mean sea-level conditions, and under projected mean sea-level conditions in 2100 according to the current range of global sea-level rise projections provided by the Intergovernmental Panel on Climate Change (IPCC 2001, Church & Gregory 2001):

1. *Storm Surge Flooding Scenarios Chosen for Modelling:* Indicative vulnerability zone mapping has been prepared for three scenarios, namely:

- *2004 predictable storm surge flood levels*: based on 0.01% exceedance storm surge water levels historically recorded by Tasmanian tide gauges (see explanation below);

- *2100 minimum predictable storm surge flood levels*: based on 2004 predictable levels *plus* minimum sea-level rise projected for 2100 by the IPCC (IPCC 2001, Church & Gregory 2001); and

- *2100 maximum predictable storm surge flood levels*: based on 2004 predictable levels *plus* maximum sea-level rise projected for 2100 by the IPCC (IPCC 2001, Church & Gregory 2001).

2. *Historic Storm Surge Flood Levels Determined:* Tidal (water level) data from Tasmanian tide gauges with a minimum of 2.7 years of valid hourly records (Stanley tide gauge), and mostly with over 5 years of valid data, were statistically analysed by Dr John Hunter[19] to obtain the 0.01% exceedance water levels for each tide gauge record (see Table 3). The 0.01% exceedance levels for each gauge do not represent the highest water levels ever recorded by each gauge, but rather the high water levels that have been exceeded by only 0.01% of the records from each gauge[20]. The 0.01% exceedance water levels represent high water events typically resulting from a combination of tides and storm surges, but not wave run-up (see Figure 1), that have a return period of the order of 2 years. For statistical purposes, high water events were considered to be discrete flood events if they were separated by at least 1 day.

   Although they typically represent a storm surge flood level slightly lower than the highest historically recorded storm surge levels at each gauge, the 0.01% exceedance water levels were chosen as the appropriate level for mapping predictable storm surge flood levels because a reasonable number of Tasmanian tide gauges (seven) had sufficiently long hourly records to allow statistically meaningful calculation of 0.01% exceedances, whereas only a couple of Tasmanian tide gauges have adequately long records as to allow meaningful calculation of smaller exceedances (i.e., higher storm surge levels with longer return periods)[21]. Thus, the 0.01% exceedance (roughly 2 year return period) water levels are the largest storm surge events for which consistent statistically-meaningful data can be extracted from enough Tasmanian tide gauge records as to be of use for State wide storm surge flood level modelling, and have thus been adopted as the indicative storm surge flood levels modelled by this vulnerability assessment.

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[19] Oceanographer, Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, Hobart. The tide gauge data analysis was conducted during March 2004. Tasmanian tide gauge records were obtained from the National Tidal Centre, Bureau of Meteorology, which is the central repository for Australian tide gauge data.

[20] For example, the 0.01% exceedance level from the Hobart tide gauge is 1.065 m AHD (from Table 3, not adjusted for sea level rise between 1972 & 2004; see discussion point 3), however the highest water level ever recorded by the Hobart gauge was somewhat higher at 1.32 m AHD, during a large storm surge on 25th July 1988 (see Table 2). The occurrence of higher water levels than the 0.01% exceedance levels is partly due to lower frequency, larger magnitude storm events, but most importantly is due to the brief occurrence of higher water levels during storm events whose duration is too short to be captured by the hourly-averaged data used for this assessment (see Figure 2 and discussion in Section 2.2).

[21] Hourly tide gauge records covering a minimum of 2.7 years (Stanley), and mostly over five years (see Table 3), were obtained from the Georgetown, Spring Bay (Triabunna), Hobart, Granville Harbour, Stanley, Burnie and Devonport tide gauges, and form the basis of this storm surge flooding hazard assessment. Data record durations from tide gauges at Naracoopa and Grassy (King Island), Bramble Cove, Launceston and Port Huon were too short to be used, and in addition it is likely that water levels at the Port Huon gauge were influenced by river floods in the Huon River estuary.

3. *Indicative Storm Surge Flood Levels Adjusted for Sea-level Rise to 2004:* The 0.01% exceedance water levels were calculated relative to the Australian Height Datum (AHD), which was established in Hobart and Burnie during 1983, at the mean sea level measured at those sites for 1972. However, mean sea level has risen since 1972. Data from an historic (1840's) tide gauge at Port Arthur, and Twentieth Century data from Port Arthur and the Hobart gauge, indicate that sea level in the south east Tasmanian region has been rising relative to the land at an average rate of 1.2 mm per year since around the late 1800s (Hunter *et al.* 2003). If it is assumed this rate of sea level rise has been linear, then it can be calculated that mean sea level at Hobart has risen by 0.038 m between 1972 and 2004, so that the AHD based on mean sea level at Hobart in 1972 now lies 0.038 m below 2004 mean sea level (note that it is known that the rate of sea-level rise has actually varied over the 20th Century (Church & White 2006), hence this assumption of linear rise may introduce small errors – see further below).

   In order to adjust the 0.01% exceedance water levels to AHD, the tide gauge data were divided into two groups (Dr J. Hunter *pers. comm.*). The first group (Georgetown, Burnie, Spring Bay and Devonport) consisted of records for which the tide gauge vertical datum is well known relative to AHD. For these records, the 0.01 percentile height relative to AHD was calculated and assumed to apply to 2004 (i.e., there was no allowance for the trend in mean sea level during the recording period, probably introducing an under-estimate of extreme heights at these stations of roughly 0.02m). In addition, it is probable that these records contain some (presently unidentified) datum shifts, which would introduce typical errors of several centimetres; further analysis would be necessary to identify and rectify these problems.

   The second group (Hobart, Stanley and Granville Harbour) consisted of records for which the vertical datum is poorly known, and for which there are clear unquantifiable datum shifts. For this group, the annual median value was first subtracted from each record and the 0.01 percentile level was calculated from the result. The annual median level was assumed to be approximately the same as the "long-term mean sea level" (i.e., a linear rising trend of 1.2 mm/year (Hunter *et al.* 2003) with no other inter-annual variability), and the resultant percentile values were therefore increased by 0.038 m (the resultant increase of mean sea level above AHD from 1972 to 2004).

   The procedure used for this second group of records ignores the effect of inter-annual variability in mean sea level (other than a linear rising trend). There are three consequences of this (Dr J. Hunter *pers. comm.*). Firstly, there is an under-estimate of the total variability and therefore of the extreme levels. Secondly, there is an error if mean sea level in 1972 was not representative of "long-term mean sea level". Thirdly, an error is introduced if the rise of "long-term mean sea level" is not now the same as the estimate for the last century (1.2 mm/year). These combined errors typically lead to an under-estimate in sea level of 0.06m (Dr J. Hunter *pers. comm.*).

4. *Indicative Storm Surge Flood Levels Interpolated between Tide Gauge Stations:* The 0.01% exceedance water levels so obtained for each usable Tasmanian tide gauge record were interpolated around the coast between the tide gauge locations by establishing the "centre of gravity" (average northing and easting) of all the tide gauge stations used, then interpolating 0.01% exceedance levels in a linear fashion between tide gauges, radially around that "centre of gravity" (see Figure 18 and Figure 19). Whilst the actual variation in water levels between the tide gauges may be slightly different to this interpolation, no additional actual data is available to establish or model water levels around the State in a more precise fashion than has been adopted here. Any (undeterminable) differences between actual water levels and the levels interpolated for this assessment are likely to be only of the order of centimetres.

5. *Coast Divided into Segments for Storm Surge Flood Level Modelling Purposes:* The Tasmanian coast was then divided into segments, radially distributed around the tide gauge "centre of

gravity", with each segment being given the interpolated indicative storm surge flood level that applies for the middle of that segment (see Figure 19). Segment angular sizes were chosen so that the indicative storm surge flood levels adopted for each adjoining segment represented steps of 0.1 metre height difference. This step (and angular segment) size was chosen on the basis of a trial and error determination that steps of this magnitude resulted in indicative flood area polygons generally varying by less than 25 metres horizontally in extent (i.e., the DEM grid cell size) at the boundaries between segments[22]. This means that, given the limitations on the vertical and horizontal accuracy of the DEM, it would not be meaningful to use smaller segments representing smaller interpolated water level steps, nor to attempt to map precise interpolated 0.01% exceedance water levels at every point around the coast. It also means that the possible errors in the indicative 0.01% exceedance flood levels, which may be of the order of 0.06m (see *Step 3* above), are significantly less than the degree of resolution obtainable with the 25m DEM, and thus negligible for the purposes of indicative flood vulnerability mapping using that DEM.

6. *Indicative Storm Surge Flood Areas Mapped for 2004 Scenario:* Areas of coastal land below the indicative storm surge flood level (0.01% exceedance level) for 2004 were then identified and mapped for each coastal segment using the 25m Digital Elevation Model (DEM) of Tasmania, which is attributed with heights based on AHD. The indicative storm surge flood vulnerability areas identified in this way for each coastal segment were then converted to vector polygon digital maps (shapefiles), and the shapefiles created for each segment were merged to give a whole-of-Tasmania map (shapefile *fldhz2004_gda.shp*) in which each indicative flood vulnerability polygon was attributed with the indicative storm surge flood level pertaining to that polygon and coastal segment. The outcome was a map of indicative coastal areas potentially susceptible to flooding in a 0.01% exceedance (approximately 2 year return period) storm surge event under current (2004) sea-level conditions.

7. *Indicative Storm Surge Flood Areas Mapped for 2100 Scenarios:* The same exercise was then repeated twice for the whole State, using indicative 0.01% exceedance storm surge flood levels recalculated for 2100 under the scenarios of the minimum and maximum global sea-level rise projections provided by the IPCC (IPCC 2001, Church & Gregory 2001). That is, the 2004 indicative (0.01% exceedance) storm surge flood levels for each coastal segment were increased by the minimum and maximum IPCC projections of sea-level rise between 2004 and 2100, to give minimum and maximum indicative (0.01% exceedance) storm surge flood levels for 2100. The resulting shapefiles are: *fldhz2100min_gda.shp* and *fldhz2100max_gda.shp* (see Appendix 2).

   The current minimum and maximum average global sea-level rise projections provided by the IPCC (IPCC 2001, Church & Gregory 2001) are for a minimum rise of 0.09 metres and a maximum rise of 0.88 metres to occur between 1990 and 2100. However, since the 2004 indicative storm surge flood level used for this assessment has already been adjusted for sea-level rise up to 2004 (see *Step 3* above), it is necessary to adjust the IPCC figures to give the projected sea-level rise between 2004 and 2100 only. Most of the IPCC predictions indicate an acceleration of sea-level rise during at least part of the 21st Century, not a simple linear rise. Based on Church & Gregory (2001, Fig. 11.12, p. 671) the IPCC minimum and maximum projections of global average sea-level rise between 2004 and 2100 are 0.08m and 0.84 m respectively. These two figures were added to the 2004 (0.01% exceedance) indicative storm surge flood levels for each coastal segment to give the minimum and maximum 2100 (0.01% exceedance) indicative storm surge flood levels, respectively, for each segment.

[22] Test - plotting of flood vulnerability zones using two vertical levels 0.1m apart at several typical low-profile coastal sites rarely produced indicative vulnerability zones varying in extent by more than 25 metres horizontally (the DEM grid cell size), whereas test - plotting of flood vulnerability zones using greater vertical level differences (of 0.2 to 0.5m) in some cases yielded vulnerability zones varying significantly in horizontal extent, by over 50 – 100 metres (multiple grid cells).

Storm Surge Flood Level Modelling Limitations and Caveats

The following limitations and caveats apply to the mapping of indicative storm surge flood vulnerability areas as described above:

- The indicative storm surge flood levels used in this assessment do not include the effects of wave run-up, which is generally not measured by tide gauges (see Figure 1). Some wave set-up effect (see Figure 1) may be included in some tide gauge records, however this is likely to be minor as most tide gauges are located in relatively sheltered harbours. The degree of additional flooding due to wave set-up and wave run-up that might occur at any specific site is partly dependant on the local topography and exposure to wave energy, which are *Regionally and Locally Variable Vulnerability Factors* (see Section 2.2) that a site-specific flood vulnerability assessment should take into account.

- For the tide gauges at Georgetown, Burnie, Spring Bay and Devonport, where the vertical datum is well known, extreme sea levels are typically under-estimated by 0.02m. For the remaining tide gauges (Hobart, Stanley and Granville Harbour), where the vertical datum is poorly known, extreme sea levels are typically under-estimated by 0.06m (Dr J. Hunter *pers. comm.*).

- All 0.01% exceedance levels were based on hourly averaged sea levels. However it is known (see Section 2.2) that some regions (e.g., south-eastern Tasmania) exhibit sea-level oscillations with a period of less than one hour, which are presumably meteorologically-driven. These could give rise to flooding events higher than those indicated (typically by 0.05m), but of less than one hour duration (Dr J. Hunter *pers. comm.*).

- The indicative flood vulnerability areas mapped pertain to 0.01% exceedance (approximately 2 year return period) flood levels. Consequently, higher flood levels than these have been historically recorded at most Tasmanian tide gauges, hence it is possible that less frequent (longer return period) floods may inundate coastal areas more extensively than those mapped by this indicative vulnerability assessment.

- For the purposes of this assessment, it has been conservatively assumed that sea-level rise will simply raise the level of potential storm surge floods (indicative 0.01% exceedance floods with approximately 2 year return periods) by a height equivalent to the rise in sea level only. There is a possibility that climate change could in future result in storm surges of a given return period becoming more intense and thus yielding an increased water level greater than simply the rise in sea level, however there is currently a lack of evidence as to whether or not this is occurring in the Tasmanian region (see Section 2.2).

- Because adequate tide gauge records are only available for seven sites around the Tasmanian coast, it has been necessary to interpolate indicative storm surge flood levels between these sites. Whilst the actual variation in water levels between the tide gauges may be slightly different to this interpolation, no additional actual data are available to establish water levels around the State in a more precise fashion than has been adopted here. Any (undeterminable) differences between actual water levels and the levels interpolated for this assessment are likely to be only of the order of centimetres.

Station	Years of record[1]	No. Hourly records	Annual Median removed?[3]	Mean Sea Level (MSL) – AHD difference for 2004 (metres)[4]	0.01% exceedance level above annual median (metres)	Calculated return period for 0.01% exceedance event (years) [5]	**0.01% exceedance level for 2004** (metres above AHD)[6]	**Minimum 0.01% exceedance level for 2100** (m above AHD)[7]	**Maximum 0.01% exceedance level for 2100** (m above AHD)[8]
Hobart	1960-2001	250,002	Yes	0.038	1.065	3.2	**1.103**	**1.183**	**1.943**
Georgetown	1965-1997	252,512	No	-	-	1.4	**1.783**	**1.863**	**2.623**
Burnie	1952-2003	273,484	No	-	-	1.2	**1.812**	**1.892**	**2.652**
Spring Bay	1985-2003	156,214	No	-	-	2.0	**0.907**	**0.987**	**1.747**
Devonport	1965-2002	156,093	No	-	-	1.5	**1.827**	**1.907**	**2.667**
Stanley	1965-1969	23,230	Yes	0.038	1.70	2.7	**1.738**	**1.818**	**2.578**
Granville Harbour	1974-1994[2]	36,825	Yes	0.038	1.375	2.1	**1.413**	**1.493**	**2.253**

Notes:

1. Total period includes gaps for some records, but all records include a minimum of 2.7 years of hourly data.
2. Granville Harbour: 4.2 years of actual record only
3. For stations where the annual median has been removed, it is assumed that the median sea level is the same as mean sea level.
4. Where annual median sea level has been removed from the data, this is the calculated sea-level rise at Hobart since AHD was established as mean sea level at Hobart and Burnie for 1972 (not calculated from the same data as the 0.01% exceedances, but rather from Hunter *et al.* 2003). In the absence of mean sea-level data for Stanley and Granville Harbour, it is assumed that the same rise of sea level above AHD has occurred (this will introduce errors of the order of centimetres).
5. Return period is calculated by determining the number of 0.01% exceedance events over the period of actual data recording. Discrete exceedance events are considered to be events separated by a minimum of 1 day. The calculated return period is more statistically reliable for the longer data records.
6. This is the final 0.01% exceedance storm surge event level above AHD, adjusted for 2004 mean sea level, that is used to map indicative flooding vulnerability zones for 2004. For stations where the annual median was removed, the figure is the 0.01% exceedance level above the annual median sea level plus the estimated height of mean sea level above AHD for 2004 (0.038m).
7. 2004 0.01% exceedance level above AHD plus 0.08 m (minimum IPCC (2001) projected sea-level rise between 2004 & 2100).
8. 2004 0.01% exceedance level above AHD plus 0.84 m (maximum IPCC (2001) projected sea-level rise between 2004 & 2100).

Table 3: Summary of Tasmanian Tide Gauge Data used to map indicative 0.01% exceedance storm surge flood vulnerability zone

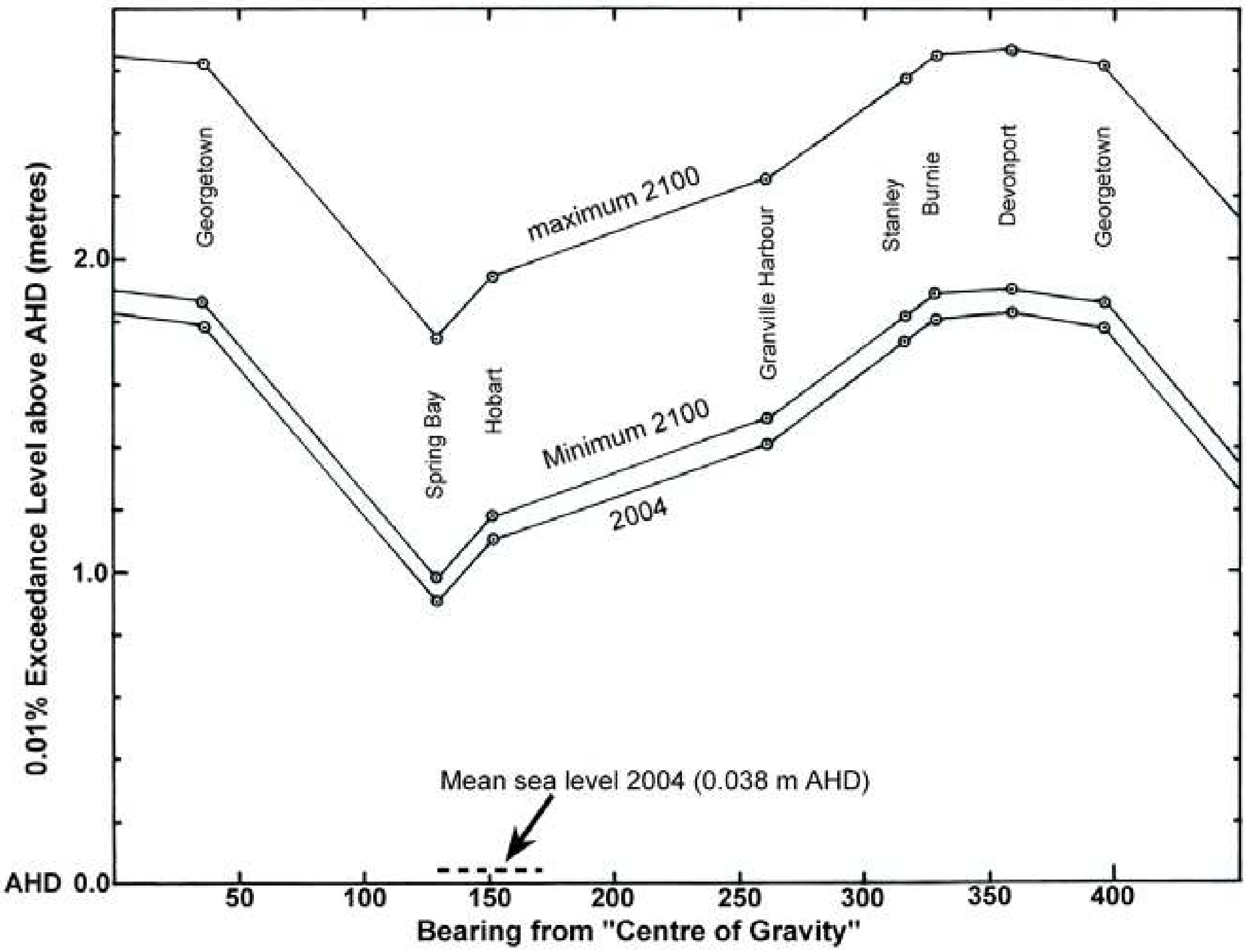

Figure 18: Predictable storm surge flood levels around the Tasmanian coast, based on measured 0.01% exceedance storm surge events at seven Tasmanian tide gauges, and linear interpolation between these gauges radially around their "Centre of Gravity" at 448 200mE 5391 600mN (GDA94). Bearings around the "Centre of Gravity" are degrees True. See Figure 19 and Table 4. The 0.01% exceedance water levels above AHD are shown adjusted (for sea-level rise) to 2004 and to the minimum and maximum IPCC (2001) projections for global sea-level rise to 2100.

Tide Gauge Station	**Easting (GDA94)**	**Northing (GDA94)**	**Bearing from COG** (True°)
Hobart	527 600	5251 800	151
Georgetown	487 200	5445 800	36
Burnie	408 800	5455 100	329
Spring Bay	576 400	5289 100	129
Devonport	446 800	5441 100	359
Stanley	356 500	5485 800	317
Granville Harbour	334 300	5372 600	261
"Centre of Gravity"	448 200	5391 600	-

Table 4: Map co-ordinates of the Tide Gauge Stations used in this assessment, and of the "Centre of Gravity" (average northing and easting) of the stations. Map co-ordinates are metric co-ordinates (MGA Zone 55), based on the GDA94 datum, and are rounded to the nearest 100 metres. "Bearing from COG" is the bearing of each station from the Centre of Gravity (COG) of the stations, in degrees from True North.

Segment (bearing True° around "Centre of Gravity")	Central 0.01% exceedance AHD (m) **2004**	Central 0.01% exceedance AHD (m) **Minimum 2100**	Central 0.01% exceedance AHD (m) **Maximum 2100**
40° - 50°	1.70	1.78	2.54
50° - 62°	1.60	1.68	2.44
62° - 70°	1.50	1.58	2.34
70° - 82°	1.40	1.48	2.24
82° - 92°	1.30	1.38	2.14
92° - 103°	1.20	1.28	2.04
103° - 112°	1.10	1.18	1.94
112° - 123°	1.00	1.08	1.84
123° - 133°	0.90	0.98	1.74
133° - 145°	1.00	1.08	1.84
145° - 165°	1.10	1.18	1.94
165° - 205°	1.20	1.28	2.04
205° - 241°	1.30	1.38	2.14
241° - 270°	1.40	1.48	2.24
270° - 286°	1.50	1.58	2.34
286° - 301°	1.60	1.68	2.44
301° - 320°	1.70	1.78	2.54
320° – 400° (= 40°)	1.80	1.88	2.64

Table 5: Table of Tasmanian coastal segments, giving the bearings (°T) of each segment boundary radially around the "Centre of Gravity" of the tide stations, and the central interpolated 0.01% storm surge exceedance levels for the centre of each segment. See also Figure 19. These central 0.01% exceedance levels have been used to map the indicative flood vulnerability zones for each coastal segment.

- As noted in Section (4.2), the 25m Digital Elevation Model that was used to identify areas below indicative storm surge flood levels is itself based only upon interpolation between available 10m LIST contour mapping in many areas and spot heights in some areas. However closer (5m) contour spacings have been used in certain areas where 1:5,000 topographic mapping exists. Since all indicative flood vulnerability zones lie on low-relief ground below the 10m AHD contour, this means that in those areas where 1:5,000 mapping or spot height data have not been used, the interpolation between the 0 m and the 10m contour AHD may introduce significant height errors into the DEM for these areas. Vertical DEM accuracy is likely to be no better than 2 metres in many such areas. However, 1:5,000 mapping is available for many urban areas where floods are likely to pose the greatest risks to infrastructure, hence the DEM is somewhat more accurate for many of the more critical flood vulnerability zones, albeit still of limited accuracy.

- For the above reason, and also because the indicative flood vulnerability mapping provided by this assessment does not take into account the numerous *Regionally and Locally Variable Vulnerability Factors* that may modify the impacts of storm surge flooding at any specific coastal location (see Section 2.2), it is emphasised that the flood vulnerability mapping provided by this assessment is indicative only. This indicative vulnerability assessment simply identifies coastal locations that may be susceptible to storm surge flooding now or in the future. In each case, a more detailed site specific assessment, including detailed topographic surveys and assessment of other *Regionally and Locally Variable Vulnerability Factors*, will be necessary to achieve a higher-confidence assessment of flooding vulnerability at any particular site.

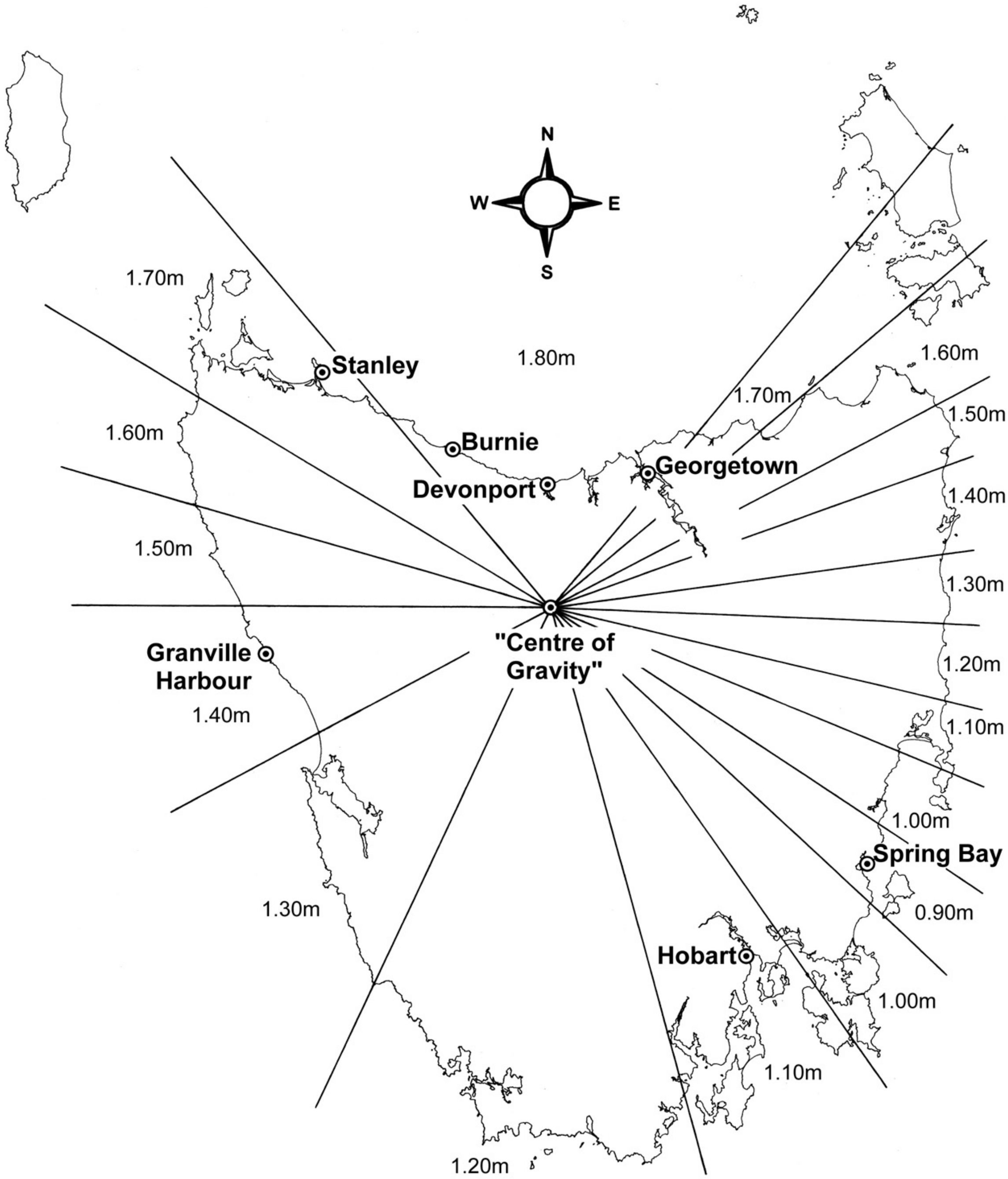

Figure 19: Map of the Tasmanian coastline, showing tide gauge station locations, and the radial segments into which the coast has been divided for vulnerability mapping purposes. Segment sizes and boundaries are based on 0.1m "jumps" in the interpolated 0.01% exceedance water levels shown on Figure 18. The 2004 0.01% exceedance storm surge flood levels mapped within each segment are indicated (see also Table 5).

- Due to limitations in the 25m DEM used for this assessment (see above and Section 4.2) it is possible that there may be additional coastal areas of limited extent which are prone to storm surge flooding, but which have not been identified as such by this assessment.

Projected Storm Surge Level Maps
Vector polygon maps were created as ESRI Arcview shapefiles for each of the three storm surge flood level scenarios listed in *Step 1*, by the method described above. Each map covers the whole of the Tasmanian coast including the Bass Strait islands. The map shapefiles created are:

Scenario	**Map** (GDA94 datum)
2004 0.01% exceedance flood levels	*fldhz2004_gda.shp*
Minimum 2100 0.01% exceedance flood levels	*fldhz2100min_gda.shp*
Maximum 2100 0.01% exceedance flood levels	*fldhz2100max_gda.shp*

Details of each map shapefile are provided in Appendix 2. Appendix 1 provides sample extracts from these maps for selected areas of the Tasmanian coast.

Indicative areas of Tasmanian coastal regions that would predictably be flooded by 0.01% exceedance storm surge events under each of the three scenarios have been obtained by summing the areas of the indicative flood polygons created for each map (Table 6).

Scenario	Indicative flooding area*
2004 0.01% exceedance storm surge flood levels	240 km^2
Minimum 2100 0.01% exceedance storm surge flood levels	247 km^2
Maximum 2100 0.01% exceedance storm surge flood levels	328 km^2

Table 6: Indicative total Tasmanian coastal areas (including Bass Strait islands) that would be flooded by 0.01% exceedance storm surge events under each of the three scenarios considered in this assessment.

* Indicative area of flooded land above the mean high water mark as mapped by current 1:25,000 LIST topographic mapping. Calculated from map polygons using ESRI Arcview GIS software.

From examination of these maps (see examples in Appendix 1), it is noteworthy that in many flood-prone coastal locations the land area that would be flooded under the Maximum 2100 scenario is only a little greater than that which is potentially prone to flooding under the 2004 scenario. Where this is the case (for example, in the Kingston Beach / Browns Rivulet area of southern Tasmania – see Figure 21), it is generally because an area of very low-lying coastal land is present, which is bounded to landwards by a sharp break of slope above which the land rises rather more steeply. In many cases the present day sea level allows flooding of all or most of the low-lying flats during 0.01% exceedance events, to the break of slope. Although the 2100 maximum flooding scenario involves a significant rise in water levels, this extra rise creates only a minor additional area of flooding since the increased flooding depth is accommodated by only a minor horizontal extension over the more steeply-rising ground.

These well-defined low-lying coastal areas typically represent areas where Holocene (post-glacial) coastal processes – occurring at a mean sea level close to the present day level – have infilled a coastal embayment with sediment or built a low sandy spit to a level only just above sea level, and the infill or spit is backed by steeper bedrock and soil slopes. Such low areas are readily prone to storm surge flooding under present mean sea-level conditions, although the adjoining slopes typically are not. However, in some areas coastal flats grade up more gradually and any break of slope is less distinct, thus in these places there may be a more significant increase in the areas flooded under the Maximum 2100 scenario as compared to the 2004 scenario. This is the case at the Lauderdale Neck, for example (see Appendix 1, Figure 21).

4.3.3 Sandy Coasts Potentially Vulnerable to Erosion and Recession

The potential for erosion and recession of sandy shorelines to occur as a result of sea-level rise has been described in Sections (2.3) and (2.4) above. For reasons described in Section (2.3), shores composed predominantly of unconsolidated and unlithified sand typically respond to storm wave attack and sea-level rise in ways that are fundamentally different to the response of hard rock shores, or of non-sandy unlithified sediments including finer sediments (clay, silt, mud) and coarser sediments (gravel, cobbles, boulders). Hence, sandy shorelines have been treated as a distinct shoreline category in this coastal vulnerability assessment.

The *Fundamental Vulnerability Factors* characterising sandy shores potentially vulnerable to erosion and significant recession due to sea-level rise (see Sections 2.3 & 2.4) are:

- The vulnerable shores are those predominantly composed of unconsolidated sand-grade sediment in the intertidal zone (i.e., sandy beaches);

- The sandy shores are backed by low-lying (low-profile) plains underlain by unconsolidated sandy sediments in the immediate backshore, which may include coastal dune systems or may be low plains without significant dunes.

The existence of a low-lying soft sediment plain behind the beach is indicative of a potential for erosional recession of the shoreline to proceed for significant distances to landwards. Where a sandy beach is immediately backed by hard bedrock (or semi-lithified sediments such as some Tertiary-age sediment deposits) rising above sea level, the beach may still erode and be lowered or lost completely as a result of sea-level rise, but recession of the shoreline will be greatly retarded by the hard bedrock (see Section 2.10), or in the case of semi-lithified sediments will be significantly slowed (see Section 2.6)[23].

Sandy shore erosion and recession may take place in at least two broadly different coastal situations, which are each subject to a somewhat different suite of geomorphic processes and whose likely responses to sea-level rise therefore need to be described by different coastal behaviour models, namely:

- "Open" or oceanic coasts, exposed to oceanic swells and particularly storm waves (see Section 2.3); and

- Coastal re-entrant shorelines (including some sheltered estuaries and tidal channels) mostly protected from oceanic storm waves but affected by other processes including tidal currents which are not generally characteristic of open coasts (see Section 2.4).

Due to the somewhat different suites of coastal geomorphic processes that operate in these two distinct coastal environments, the types and degree of influence of *Regionally and Locally Variable*

[23] Note that the *Bedrock* attribute in the *tascsthz_v2gda* digital mapping used for this assessment allows semi-lithified bedrock types (e.g., Tertiary-age sediments) to be differentiated from the hard bedrock types.

Digital map file (shapefile): *tascsthz_v2gda* (GDA94 datum)
Attribute field: *Sandyvuln*

Attributes:		Total length (km / %)*
Not a sandy shoreline:	00	4250 km / 66%
Undifferentiated sandy shorelines: (Types not fitting categories 20, 25, 30 or 35 below. Potentially vulnerable to erosion and recession due to sea-level rise, but type undetermined.)	01	25 km / 0.5%
Open coast sandy shores backed by low-lying sandy plains: (Potential vulnerability to erosion and significant recession with sea-level rise (see Section 2.3.))	20	1129 km / 17%
Open coast sandy shores immediately backed by bedrock: (Potential vulnerability to erosion and beach lowering or loss with sea-level rise, but shoreline recession likely to be minimal over next 50-100 years, except where bedrock is only semi-lithified (in which case see Section 2.6.))	25	371 km / 5.5%
Re-entrant sandy shores backed by low-lying sandy plains: (Potential vulnerability to erosion and significant recession with sea-level rise, in ways described by coastal re-entrant behaviour models (see Section 2.4))	30	512 km / 8%
Re-entrant sandy shores immediately backed by bedrock: (Potential vulnerability to erosion and beach lowering or loss with sea-level rise, but shoreline recession likely to be minimal over next 50-100 years, except where bedrock is only semi-lithified (in which case see Section 2.6.))	35	185 km / 3%

Table 7: Indicative sandy shoreline vulnerability categories as identified by the assessment described in this section, and encoded in the *tascsthz_v2gda* digital map using the *Sandyvuln* attribute. Note that the proportion of undifferentiated sandy shorelines (attribute 01) has been significantly reduced compared to the original version of this mapping (Sharples 2004a), owing to the recognition that many of these were sandy shores backed by dunes over a rising bedrock surface – these have been re-attributed accordingly (*Backshore* attributes 31 or 34 – see Sections A 2.3.1 & A 2.3.3).

* Length at 1:25,000 map scale, including Bass Strait Islands, all other major islands, and most small islands, but not including Macquarie Island. Entire coastline length at this scale is 6472 km (slightly longer than the coastline length in the first edition of this mapping – *tascsthz* (Sharples 2004a) – due to subsequent addition of a number of coastal lagoons to the map). Percentage is the percentage of that total coastline length occupied by the specified shoreline type.

Vulnerability Factors that govern the degree, pattern and rate of erosion and recession on any specific sandy shoreline are somewhat different between these two coastal environments (see further details in Sections 2.3 & 2.4).

Mapping of Sandy Shorelines with Potential Erosion and Recession Vulnerability
The sandy shoreline indicative vulnerability assessment undertaken in this project identifies and differentiates the various categories of sandy shoreline noted above. Shores displaying the *Fundamental Vulnerability Factors* that characterise sandy shores potentially vulnerable to erosion and significant recession due to sea-level rise (as above) are identifiable from the descriptive geomorphic shoreline attributes encoded in the *tascoastgeo_v4gda* and *tascsthz_v2gda* digital mapping (see Section 4.2.1). This mapping also permits identification of sandy shores immediately backed by bedrock, and allows differentiation between open coast and re-entrant sandy shores. The descriptive attributes used to identify these different sandy shoreline types are detailed in the Data Dictionary (Appendix A2.3.1 & A2.3.3). Table 7 summarises the sandy shoreline categories as defined above that have been identified in the *tascsthz_v2gda* digital map (derived from *tascoastgeo_v4gda*) accompanying this report, using the *Sandyvuln* attribute.

The differentiation between sandy shoreline types provided by the *Sandyvuln* field attribute codes permits sandy shoreline types to be mapped as "lumped" categories in a variety of ways, for example:

Lumped category:	***Sandyvuln* Field attribute codes:**
All sandy shorelines:	01 + 20 + 25 + 30 + 35
All sandy shorelines backed by low-lying sand plains, irrespective of coastal situation (open or re-entrant): (potential for erosion and significant recession)	20 + 30
All sandy shorelines immediately backed by bedrock, irrespective of coastal situation (open or re-entrant): (potential for beach erosion and lowering or loss, but erosional recession of shorelines likely to be minimal over next 50 – 100 years except where bedrock is only semi-lithified)	25 + 35

The following points should be noted in interpreting the sandy shore indicative vulnerability mapping provided in the *Sandyvuln* attribute:

- *"Sandy Shore" definition:* "Sandy shores" have been defined as those shores with significant unconsolidated sand deposits in the upper intertidal zone. Protruding bedrock outcrops and/or pebble, cobble or boulder berms may or may not also be present.

- *Dominantly pebble or cobble beaches:* Although sandy beaches with pebble and cobble berms have been treated as sandy beaches for the purpose of this assessment, some pebble / cobble beaches have very little or no sand in the upper intertidal zone. These may behave differently to sandy beaches in response to sea-level rise – for example, the pebbles and cobbles may possibly "armour" the shore, reducing the rate of erosion and/or recession. Thus, dominantly pebble / cobble beaches with little or no sand in the upper intertidal zone have not been considered as sandy shores and are not included in the *Sandyvuln* field, even where they are backed by low-lying plains of (partly) sandy sediments, as for example at Lillico Beach in northern Tasmania (see Figure 45). The response of such shores to sea-level rise has not been investigated during this assessment (see Section 2.9).

- *Landwards extent of low-lying sandy plains backing sandy shores:* Where sandy shores are backed by low-lying sandy plains (*Sandyvuln* field attribute codes 20 & 30), the landwards extent of the low-lying sandy plain that is potentially susceptible to erosional recession has not been specified in the data set used for this assessment. The landwards extent of the low-lying sediment plain determines the degree of sandy shoreline recession that is ultimately possible, and may vary from only a few tens of metres, to over a kilometre. Interpretation of geological maps and/or site-specific field assessments are necessary to determine the landwards extent of the erodible sediments in each case.

- *Sandy coastal re-entrants not fully identified:* Several large sandy coastal re-entrants that were not included in the first edition of this vulnerability mapping (*tascsthz* – Sharples 2004a) have now been added to *tascsthz_v2gda*, for example Henderson Lagoon near Scamander. However, a number of other coastal re-entrants with sandy shores potentially susceptible to erosion and recession are still not included in the data set and indicative vulnerability mapping (*tascsthz_v2gda*) accompanying this report, because the digital Shoreline Geomorphic Types line map on which these are based (*tascoastgeo_v4gda*) still does not include them (for example, on Flinders Island and some smaller east coast lagoons). These should be ideally added to the data set in future, however their current omission from the indicative vulnerability mapping should not be taken to indicate that no potential vulnerability exists.

- *Identification of coastal re-entrants:* In the first edition of this vulnerability mapping (Sharples 2004a), coastal re-entrants were manually identified (by C. Sharples) for the purpose of classifying vulnerable sandy shores. However, the Wave Energy attribute *Wavenzn* in *tascoastgeo_v4gda* and *tascsthz_v2gda* has subsequently been supplemented with an additional attribute code ("9") that identifies coastal re-entrants not exposed to oceanic wave energies. This code is not an "Exposure" code since "sheltered" shores may occur on the open coast as well as in re-entrants (e.g., in the lee of a headland). Rather, the *Wavenzn* code "9" identifies shores effectively isolated from oceanic wave energies by having their connection to the sea only via a narrow tidal channel. This attribute effectively identifies most coastal re-entrants of the sort discussed in Section (2.4) of this report, and has been used accordingly to identify most (but not all – see below) of the coastal re-entrants identified in this mapping.

- *Tidal channels as "coastal re-entrants":* Whereas most shores identified in this assessment as "coastal re-entrants" are almost-entirely enclosed water-bodies with only narrow channels connecting to the sea (which can be identified as re-entrants using the *Wavenzn* attribute "9", as noted above), a few broad tidal passages with connections to the sea at both ends have also been manually classified (by C. Sharples) as "coastal re-entrants" in the Bass Strait area. These passages comprise some broad tidal passages near Robbins Island (NW Tas.) and Franklin Sound (southern Flinders Island). This has been done because these particular channels have comparatively sheltered sandy shores, yet experience strong tidal currents and contain large sub-tidal sand bars analogous to flood-tide deltas, hence it is likely that their geomorphic behaviour may have more in common with other coastal re-entrants (Section 2.4) than with "normal" open ocean sandy shores (Section 2.3).

Sandy Shore Vulnerability Assessment and Caveats

It is emphasised that the categorisation of sandy shoreline types, and their corresponding potential susceptibility to erosion and recession due to sea-level rise, provided by the attributes of the *Sandyvuln* field as described above, is based purely on identification of *Fundamental Vulnerability Factors* only, and constitutes simply an indicative identification of shores potentially having some (unspecified) degree of vulnerability. A variety of *Regionally and Locally Variable Vulnerability Factors* (as outlined in Sections 2.3 & 2.4) may raise or lower the potential susceptibility of particular sandy shores to erosional recession in response to sea-level rise, and can in some cases even cause a sandy shore to prograde (accrete) rather than recede (this is likely to be the case for beaches on the east coasts of King and Flinders Islands, and for the southern end of Ocean Beach (west coast), for example). For this reason, the indicative vulnerability assessment provided here must be followed up by site-specific assessments (Sections 3.3.2 and 5.0) before any final assessment of the likely patterns, rates or magnitudes of a sandy shoreline's physical response to sea-level rise can be made.

Due to limitations in the base data used for this project (see Sections 1.4 and 4.2.1), it is additionally possible that some shorelines indicatively assessed here as having an erosional recession vulnerability may have only an insignificant vulnerability, whilst some shores not identified as such may have a significant vulnerability to erosional recession.

Potential Shoreline Recession Distances and Areas

The indicative mapping of sandy shorelines vulnerable to erosional recession provided with this report (*tascsthz_v2gda* digital map, *Sandyvuln* attributes 20 & 30) only indicates which shorelines are potentially susceptible to landwards recession with sea-level rise, however it does not indicate the landwards distance to which recession might proceed over a given time period. Potential recession distances are sensitively dependant on a range of *regionally and locally variable vulnerability factors* (Sections 2.3 and 2.4) which have not been integrated into this indicative assessment, and can only be assessed by means of detailed site-specific assessments, modelling and monitoring of rates of shoreline recession over time (Sections 3.3.2 and 3.4). Notwithstanding this, however, any assessment of potential recession at any level of detail will always be subject to a degree of uncertainty, and this needs to be recognised and incorporated into coastal planning procedures (Cowell *et al.* 2006).

The horizontal distances to which shoreline recession might proceed over periods of (say) 50 to 100 years are of concern to planners and others who will typically want to define precautionary "vulnerability envelopes" to landwards of sandy shorelines that might be affected by erosional recession over future decades. Without detailed site-specific assessments, the only guideline widely available for identifying vulnerable areas to landwards of a receding shoreline is the "Rule of Thumb" often used in association with the Bruun Rule, which states that horizontal shoreline recession due to sea-level rise is most commonly in the range of 50 to 100 times the amount of vertical sea-level rise (depending primarily on the substrate gradient; see Section 2.3). Whilst this "Rule of Thumb" is obviously simplistic, and actual recession distances can be much greater or much less than this depending on local conditions, short of a detailed site-specific assessment and modelling exercise (Section 3.3.2) there are few alternative means available to provide an indication of likely landwards recession distances associated with a sandy shoreline vulnerable to erosion. In the absence of better information, this rule of thumb could be used as a basis to define a precautionary vulnerability envelope to landwards of a receding shoreline. Consideration could be given to applying a multiplier to the simple "50 – 100 x" rule of thumb, to allow for the possibility that recession may be greater than this at some sites, or that erosion may already be underway.

For example, the IPCC (2001) projects a global vertical sea-level rise of 0.09 to 0.88m between 1990 and 2100. Using the 50 to 100 times sea-level rise "Rule of Thumb", this equates to potential landwards recession of receding shorelines of anywhere between 4.5 metres (50 x 0.09m) and 88 metres (100 x 0.88m) between 1990 and 2100. Ideally, a landwards recession distance such as this should be measured from the present shoreline erosion scarp or vegetation limit (i.e., the limit of existing shoreline wave erosion), not from the mean sea-level or high tide line.

On this basis a precautionary vulnerability area or envelope behind a receding shoreline could be calculated for (say) a 50 year or 100 year period, using (say) a median or maximum prediction of sea-level rise, and such an envelope could be applied as a development restriction area in Local Council planning schemes. This type of approach has been taken in the Western Australian State Coastal

Planning Policy, which uses a multiplier of 100 x sea-level rise to define setback lines (Western Australian Planning Commission 2001). One possibility for applying such a precautionary vulnerability zone would be that proponents wishing to develop within such a defined zone would need to undertake sufficient site-specific assessments of recession vulnerability at their site as to demonstrate that their development is in fact not at risk, or that their development can be designed in such a way as to cope with any recession hazard without creating unacceptable adverse effects on other environmental values.

However, even in cases where detailed site-specific assessments and coastal behaviour modelling procedures have been applied to a particular beach, it is inevitable that a range of uncertainties over future recession distance and rates will remain unresolved. Prediction of specific recession distances in a deterministic fashion tends to give a misleading impression of certainty, and hence Cowell *et al.* (2006) advocate forecasting possible future impacts on beaches in terms of the differing probabilities of varied degrees of change in order to make the uncertainties involved more transparent.

4.3.4 Muddy Shores Potentially Vulnerable to Change

Whereas sandy shores are undoubtedly the most easily eroded and mobile shoreline type, a variety of other shoreline substrates are also readily eroded. These latter are treated separately to sandy shores in this indicative vulnerability mapping because they display significantly different geomorphic behaviour. This section describes the indicative mapping of muddy-silty shores (described in Section 2.5). These are a distinctive class of soft erosion-prone shores, typically found in sheltered estuarine and deltaic environments, which are likely to respond to climate change and sea level rise in somewhat different ways to other soft erodible shores (i.e., sandy shores or the soft clayey-gravelly "bedrock" shores described in Sections 2.6 & 2.7, and Section 4.3.5 following).

The *Fundamental Vulnerability Factor* identifying shores vulnerable to those changes characteristic of muddy shores is:

- Shorelines dominated by soft unconsolidated dominantly muddy – silty grade sediment in the upper intertidal zone (and usually extending into the subtidal zone).

Muddy shores may be only a zone of muddy sediment in the intertidal to sub-tidal zone, backed by harder bedrock backshores, or the muddy sediment may be backed by extensive soft muddy backshore ("supratidal") mudflats above the Mean High Water Mark. In both cases the soft intertidal zone sediment is prone to significant change with sea level rise or other local changes, however where extensive supratidal mudflats are present in the backshore area there is potential for considerable erosional recession of the soft shores. Since data suitable for separating these two classes of muddy shores is readily available in the *tascsthz_v2gda* dataset, and the consequence of the difference may be considerable, the indicative mapping of muddy shores has been classified into these two types.

Mapping of Muddy Shorelines Vulnerable to Change

Coasts displaying the *Fundamental Vulnerability Factors* that define muddy shorelines potentially vulnerable to change (as above) are identifiable from the descriptive geomorphic shoreline attributes encoded in the *tascoastgeo_v4gda* and *tascsthz_v2gda* digital mapping (see Section 4.2.1). The descriptive attributes used to identify these muddy shorelines are detailed in the Data Dictionary (Appendix A2.3.1 & A2.3.3). Muddy shorelines as defined above have been identified in the *tascsthz_v2gda* digital map (derived from *tascoastgeo_v4gda*) accompanying this report using the *Muddyvuln* attribute:

Digital map file (shapefile): *tascsthz_v2gda* (GDA94 datum)_
Attribute field: *Muddyvuln*

Attributes:		Total length (km / %)*
Not a muddy shoreline:	00	6014 km / 93%
Soft muddy shores backed by extensive low-lying unconsolidated sediment plains: (Potentially vulnerable to significant change with sea-level rise, including significant erosional recession)	10	258 km / 4%
Soft muddy shores mainly backed by bedrock: (Potentially vulnerable to limited change except where bedrock is colluvium-mantled or is semi-lithified bedrock)	20	200 km / 3%

Table 8: The extent of soft muddy shorelines on the Tasmanian coastline with indicative vulnerability to changes with sea-level rise and climate change, as encoded in the *Muddyvuln* attribute of the *tascsthz_v2gda* indicative coastal vulnerability map of Tasmania (see Appendix section A2.3.3).

* Length at 1:25,000 map scale, including Bass Strait Islands, all other major islands, and most small islands, but not including Macquarie Island. Entire coastline length at this scale is 6472 km (slightly longer than the coastline length in the first edition of this mapping – *tascsthz* (Sharples 2004a) – due to subsequent addition of a number of coastal lagoons to the map). Percentage is the percentage of that total coastline length occupied by the specified shoreline type.

4.3.5 Soft Clayey-Gravelly or Colluvial Shores Vulnerable to Progressive Erosional Recession and / or Slumping

This section describes the indicative mapping of a further class of soft erodible shoreline, namely soft "clayey-gravelly" bedrock or colluvial (unconsolidated slope deposit) shores which are prone to progressive wave erosion and/or slumping. Although these vulnerabilities were described separately in Sections (2.6) & (2.7), they have been mapped together using the *Erosvuln* attribute of the *tascsthz_v2gda* map, since it is evident that the same types of soft clayey-gravelly shoreline substrate prone to progressive erosion on low-profile coasts are also typically prone to slumping on steeper coastal profiles.

A key feature of soft clayey-gravelly or colluvial shores is that – unlike sandy shores which may repeatedly erode then accrete or "grow back" – these shores will only erode and progressively retreat, they do not accrete. Nor do these shores have the potential to rebuild as a result of silt influx from rivers, as some estuarine or deltaic "muddy – silty' shores may do. The types of soft clayey-gravelly or colluvial shores described in Sections (2.6) & (2.7) are prone to progressive ongoing wave erosion or slumping even with a stable sea level, but their erosion and slumping is likely to accelerate with sea-level rise.

The *Fundamental Vulnerability Factors* identifying shores susceptible to progressive erosion and / or slumping are:

- shorelines whose immediate backshore zones are composed of unconsolidated slope deposits (colluvium), or of semi-lithified, deeply weathered or intensely fractured substrates (clayey-gravelly bedrock), where that substrate is exposed to storm wave erosion and is not mantled by sand or other coastal sediment.

and in the case of shores prone to slumping:

- shorelines having a moderately-angled to steep (or cliffed) coastal profile rising directly from the zone of storm wave attack.

Where shorelines correspond to the first vulnerability factor above (substrate type), but have only a low flat coastal profile, they have been classified as indicatively prone to progressive erosion only. However, where the same substrates constitute moderately to steeply sloping backshore slopes, they are classified as being prone to both progressive erosion and slumping.

Mapping of Shorelines Vulnerable to Progressive Erosional Recession and/or Slumping
Coasts displaying the *Fundamental Vulnerability Factors* that define shorelines potentially vulnerable to progressive erosion and/or slumping (as above) are identifiable from the descriptive geomorphic shoreline attributes encoded in the *tascoastgeo_v4gda* and *tascsthz_v2gda* digital mapping (see Section 4.2.1). The descriptive attributes used to identify these shorelines are detailed in the Data Dictionary (Appendix A2.3.1 & A2.3.3). Shores vulnerable to progressive erosion and/or slumping as defined above have been identified in the *tascsthz_v2gda* digital map (derived from *tascoastgeo_v4gda*) accompanying this report using the *Erosvuln* attribute:

Digital map file (shapefile): *tascsthz_v2gda* (GDA94 datum)
Attribute field: *Erosvuln*

Attributes:		Total length (km / %)*
Not a soft clayey – gravelly or colluvial shore shoreline:	00	6118 km / 95%
Low profile soft clayey – gravelly shore: (Potentially vulnerable to progressive erosional recession)	10	141 km / 2%
Moderately to very steep or cliffed soft clayey – gravelly or colluvial shore: (Potentially vulnerable to progressive erosional recession and to slumping)	20	213 km / 3%

Table 9: The extent of soft clayey – gravelly or colluvial shorelines on the Tasmanian coastline with indicative vulnerability to progressive erosional recession and / or to slumping with sea-level rise and climate change, as encoded in the *Erosvuln* attribute of the *tascsthz_v2gda* indicative coastal vulnerability map of Tasmania (see Appendix Section A2.3.3).

* Length at 1:25,000 map scale, including Bass Strait Islands, all other major islands, and most small islands, but not including Macquarie Island. Entire coastline length at this scale is 6472 km (slightly longer than the coastline length in the first edition of this mapping – *tascsthz* (Sharples 2004a) – due to subsequent addition of a number of coastal lagoons to the map). Percentage is the percentage of that total coastline length occupied by the specified shoreline type.

Comparison with Other Coastal Landslide Hazard Assessments and Landslide Inventories

Mineral Resources Tasmania (Department of Infrastructure, Energy & Resources) has over many years undertaken mapping of landslides and assessment of landslide hazards throughout Tasmania, including in coastal areas. A recent outcome of this work has been the production of predictive landslide hazard maps for the Hobart and Launceston regions (Mazengarb 2004a, b; 2006). These maps were prepared using a modelling process described by Mazengarb (2005), which involved acquiring detailed geological and geomorphic mapping data, including inventories of past landslide activity, then applying computerised modelling techniques to identify areas having the characteristics pre-disposing them to landslides (a method similar in principle to the first – pass coastal vulnerability assessment described in this report, but more detailed in practice).

The landslide hazard maps for Hobart and Launceston regions prepared by Mineral Resources Tasmania (MRT: Mazengarb 2004a, b; 2006) include coastal landslide hazard areas, and comparison of these with the coastal slump vulnerability zones indicated by the first pass assessment described in this report (*Erosvuln* attribute of the *tascsthz_v2gda* indicative coastal vulnerability map of Tasmania) show an excellent correspondence, thereby providing a successful test of the methodology applied to create these maps.

The only near-coastal landslide hazard zones in the MRT mapping for these areas that were not indicated by the *Erosvuln* attribute were certain slump-prone slopes in the Tamar estuary that are separated from the High Water Mark by at least 100 metres width of low muddy tidal and supratidal flats. These were not indicated by the *Erosvuln* attribute because – under the mapping protocols adopted for the shoreline geomorphic map underlying the *Erosvuln* attribute (see Appendix 2) – the upper intertidal and backshore zones in those areas are mapped as "muddy-silty" shores and backshore flats, with the steeper slump-prone slopes behind the muddy flats being regarded as non-shoreline features for the purpose of the shoreline geomorphic map *tascoastgeo_v4gda.shp* and *tascsthz_v2gda.shp*. In fact, these shores appear as vulnerable shores in the muddy-silty vulnerability category (*Muddyvuln* attribute) rather than in the slump-prone category (*Erosvuln* attribute).

However, comparison of an initial iteration of the *Erosvuln* attribute with Mineral Resources Tasmania mapping[24] of previous landslides along the Boat Harbour to Devonport section of the north coast of Tasmania showed a poor correspondence. The cause of this problem was traced to the fact that much of the shoreline geomorphic map (*tascoastgeo_v4gda* / *tascsthz_v2gda*) *Backshore* attributes for this stretch of coast were based on older geological mapping which suggested backshore areas formed of "hard" bedrock + soil slopes, whereas in many places there are actually extensive (but mainly vegetated) colluvial deposits and deeply weathered basalts running down to the shoreline. These materials are highly prone to slumping, and numerous coastal landslides have occurred along this coastal strip.

Mineral Resources Tasmania is currently (2005 – 2006) undertaking new 1:25,000 scale geological mapping of this stretch of coast, preparatory to creating Landslide Hazard maps for the region. Draft copies of the new geological mapping (primarily undertaken by C. Calver & J. Everard, Mineral Resources Tasmania) were provided to C. Sharples, and have been used to update the *Backshore* attribute of the geomorphic line map (*tascoastgeo_v4gda* / *tascsthz_v2gda*). This allowed a new iteration of the *Erosvuln* slump vulnerability attribute to be generated, which now indicates coastal slump vulnerability zones for the north coast strip which in most places correspond well with mapping of past coastal landslides.

It should be noted, however, that there do remain a small handful of recorded coastal landslides on both the north coast and also in the Derwent estuary region, which do not correspond with slump vulnerability zones identified by the *Erosvuln* attribute. It is likely that in these cases the mapping of

[24] Provided to C. Sharples by Mineral Resources Tasmania as untitled digital mapping.

Backshore types requires updating based on ground-truthing. The writer is also aware of shoreline colluvial (slump) deposits – mostly associated with cliffs – on Tasman Peninsula which are not shown on any available mapping and which have not yet been incorporated into the *tascoastgeo_v4gda* / *tascsthz_v2gda* shoreline geomorphic maps. These also would be identified as coastal slump zones if the shoreline geomorphic mapping were updated by ground-truthing; however, most of the latter coastal segments do appear as coastal sea cliff rock-fall vulnerability zones under the *Cliffvuln* attribute (see Section 4.3.6 below).

Time has not permitted the work necessary to correct these latter known omissions from the *Erosvuln* slump vulnerability attribute; however, these minor exceptions serve to highlight once again the fact that the *Erosvuln* vulnerability category constitutes only an <u>indicative</u> assessment of coastal vulnerability to slumping which can only be as accurate as its underlying base data, and that all coastal locations for which any actual development is proposed will require a more detailed site-specific assessment of vulnerabilities prior to undertaking any development works (see also discussion in Section 3.2).

4.3.6 Coasts Vulnerable to Hard-Rock Sea Cliff Rock Falls and Retreat

The potential for coastal cliffs ("sea cliffs") exposed to wave action to undergo continuing erosion has been described in Section (2.8). Sea cliff erosion is an ongoing process even without sea-level rise, but is likely to be accelerated by sea-level rise and also by any increased storminess resulting from climate change. Sea cliff erosion may result in rock falls, collapses, slumping and progressive cliff-line retreat.

The *Fundamental Vulnerability Factor* identifying shorelines susceptible to sea cliff erosion and retreat:

- The presence of a vertical cliff in hard lithified bedrock rising above the high water mark and exposed to storm wave action. A shore platform, talus apron or narrow intertidal sandy or cobble beach may or may not be present at the base of the cliff; however the cliff base (or talus apron at the cliff base) is reached by waves during large storms, at least.

This vulnerability category refers to sea cliffs rising to greater than a nominal height of 5 metres; small cliffs below 5m height are not identified as such in the *tascoastgeo_v4gda* and *tascsthz_v2gda* data sets, and are mostly classified simply as rocky shorelines.

This vulnerability category is focussed on cliffs composed of hard lithified bedrock. Cliffs do occur in semi-lithified bedrock shores (especially shores eroded into Tertiary-age sedimentary sequences, for example at Macquarie Harbour), however this type is instead included in the "soft clayey-gravelly or colluvial shores prone to progressive erosion and/or slumping" vulnerability category (Section 4.3.5 above), as such cliffs are likely to respond to wave action in ways more characteristic of the latter category (see also discussion in Section 2.8).

For the purposes of this vulnerability assessment, hard rock cliffs potentially vulnerable to rock falls and erosional retreat have been sub-divided into sub-categories more and less exposed to wave energy. Whilst doing so constitutes a partial "Second Pass" vulnerability assessment (as defined in Section 3.3.1), differences in exposure are likely to significantly affect sea cliff hazards (see Section 2.8). However, a pure "First Pass" indicative vulnerability assessment (as defined in Section 3.2) can be obtained by simply lumping these sub-categories together.

Mapping of Cliffed Shorelines Vulnerable to Rock Falls and Retreat

Coasts displaying the *Fundamental Vulnerability Factors* that define cliffed shorelines potentially vulnerable to rock falls and retreat (as above) are identifiable from the descriptive geomorphic shoreline attributes encoded in the *tascoastgeo_v4gda* and *tascsthz_v2gda* digital mapping (see Section 4.2.1). The descriptive attributes used to identify these cliffed shorelines are detailed in the Data Dictionary (Appendix A2.3.1 & A2.3.3). Cliffed shorelines as defined above have been identified in the *tascsthz_v2gda* digital map (derived from *tascoastgeo_v4gda*) accompanying this report using the *Cliffvuln* attribute (see Table 10):

Digital map file (shapefile):	*tascsthz_v2gda*	(GDA94 datum)
Attribute field:	*Cliffvuln*	

Attributes:		Total length (km / %)*
Not a cliffed shoreline:	00	5113 km / 79%
Exposed hard-rock cliffed shoreline: (higher potential vulnerability to rock falls, collapse, slumping and cliff retreat)	10	1216 km / 19%
Sheltered hard-rock cliffed shoreline: (lower potential vulnerability to rock falls, collapse, slumping and cliff retreat)	20	143 km / 2%

Table 10: The extent of hard-rock cliffed shorelines on the Tasmanian coastline with indicative vulnerability to rock falls and cliff retreat, as encoded in the *Cliffvuln* attribute of the *tascsthz_v2gda* indicative coastal vulnerability map of Tasmania (see Appendix section A2.3.3).

* Length at 1:25,000 map scale, including Bass Strait Islands, all other major islands, and most small islands, but not including Macquarie Island. Entire coastline length at this scale is 6472 km (slightly longer than the coastline length in the first edition of this mapping – *tascsthz* (Sharples 2004a) – due to subsequent addition of a number of coastal lagoons to the map). Percentage is the percentage of that total coastline length occupied by the specified shoreline type.

4.3.7 Minimal Vulnerability Rocky Shorelines

Shores presenting minimal vulnerability to geomorphic hazards associated with climate change and sea-level rise are those on which little noticeable geomorphic change is likely to occur within the medium term future (eg, 50 to 100 years), and on which the other hazards discussed in this report (e.g., storm surge flooding) are unlikely to present significant risks for infrastructure or development within the next 50 to 100 years.

Shorelines defined as Minimal Vulnerability shorelines for the purposes of this assessment are those with the following *Fundamental Minimal Vulnerability Factors* (see also Section 2.10):

- Hard rock (erosion-resistant) shorelines (not including narrow sandy intertidal zones immediately backed by bedrock backshores[25]). Tertiary-age sedimentary bedrock is not considered a hard rock shoreline as some Tertiary sediment bedrock is only semi-lithified and is easily erodible (see Section 2.6) and/or is prone to slumping (see Section 2.7).

- Rocky backshores rising on gentle to moderately steep slopes from High Water Mark (minimal flooding potential).

- Neither vertical sea cliffs (greater than 5 metres high), nor bedrock with significant colluvial or talus (slope) deposits in the backshore (which may be subject to block collapse or slumping)

Low cliffs or scarps less than 5 metres high and/or wave cut rocky shore platforms may or may not be present[26].

The types of sloping bedrock shores described above are likely to show little physical change with rising sea levels over the next century or so, apart from slightly higher tide lines in accordance with the projected vertical rise in sea level. Some erosional change is likely to occur over longer time frames (100+ years).

It should be noted that there are highly likely to be other shorelines, not identified by this assessment, which will turn out on further investigation (including ground-truthing) to present minimal vulnerability resulting from sea-level rise and climate change. Similarly, due to limitations in the base data used for this project (see Sections 1.4 and 4.2.1), it is also possible that some shorelines identified here as "Minimal Vulnerability" will be shown by a site specific assessment to present some type or level of vulnerability that could not be identified by this "indicative" assessment. For example, some rocky shores identified as "minimal vulnerability" on the basis of the available data, could turn out on field inspection to be intensely fractured and weathered bedrock, or may have colluvial or talus deposits not identified by existing mapping. These could present a potential coastal slump

[25] Narrow sandy shores immediately backed by bedrock could arguably be regarded as minimal hazard shorelines since there is little potential for significant erosional recession of the backshore. However they are excluded here since it is likely that significant erosion of sand in the intertidal zone itself will occur, resulting in noticeable geomorphic changes including possible complete loss of the beach, with consequences for shoreline aesthetics, recreational amenity and ecology. Such shorelines are identified by the *Sandyvuln* attribute field (see Section 4.3.3 above).

[26] The presence of such features may be indicative of a faster rate of change in response to sea level rise, but such a rate of change is still likely to be slow in comparison to other shoreline types, and unlikely to be a significant hazard for infrastructure or other coastal uses within 50 to 100 year periods (see Section 2.10).

vulnerability (see Section 2.7) that was not previously identified due to lack of mapping of such slump-prone materials.

Mapping of Minimal Vulnerability Shorelines
Coasts displaying the *Fundamental Minimal Vulnerability Factors* that define Minimal Vulnerability shorelines (as above) are identifiable from the descriptive geomorphic shoreline attributes encoded in the *tascoastgeo_v4gda* and *tascsthz_v2gda* digital mapping (see Section 4.2.1). The descriptive map attributes used to identify these Minimal Vulnerability shorelines are detailed in the Data Dictionary (Appendix Section A2.3.12 & A2.3.3). Minimal vulnerability shorelines as defined above have been identified in the *tascsthz_v2gda* digital map (derived from *tascoastgeo_v4gda*) accompanying this report, using the *Minvuln* attribute (see Table 11).

Digital map file (shapefile): *tascsthz_v2gda* (GDA94 datum)
Attribute field: *Minvuln*

Attributes:		Total length (km / %)*
Not a Minimal Vulnerability shoreline:	00	5213 km / 81%
Minimal Vulnerability shoreline:	01	1259 km / 19%

Table 11: The extent of indicative minimal vulnerability shorelines (sloping hard bedrock shores) on the Tasmanian coastline, as encoded in the *Minvuln* attribute of the *tascsthz_v2gda* indicative coastal vulnerability map of Tasmania. Note that the length of coastline now recognised as having minimal vulnerability is slightly greater (by 80 km or ~1%) than previously identified by Sharples (2004a). This is the result of additional ground-truthing in some areas, and the recognition of two additional shoreline types having minimal vulnerability to erosion and flooding (see Appendix section A2.3.3).

* Length at 1:25,000 map scale, including Bass Strait Islands, all other major islands, and most small islands, but not including Macquarie Island. Entire coastline length at this scale is 6472 km (slightly longer than the coastline length in the first edition of this mapping – *tascsthz* (Sharples 2004a) – due to subsequent addition of a number of coastal lagoons to the map). Percentage is the percentage of that total coastline length occupied by the specified shoreline type.

4.3.8 Unclassified Vulnerability Shorelines

Those shores which have not been indicatively classified into any coastal geomorphic vulnerability classification, or as having minimal vulnerability, have been identified using the *Unclass* attribute in *tascsthz_v2gda*. See Appendix 2 Data Dictionary (Sections A2.2.1 & A2.3.3).

The general distribution of unclassified shores around Tasmania is shown on Figure 50. The total length of the Tasmanian shoreline remaining to be classified into one of the coastal vulnerability categories discussed in the preceding sub-sections (including the minimal vulnerability category) is as shown in Table 12.

Many of these remaining unclassified shoreline types have cobble / boulder "beaches" lacking in sand. The response of these types to sea-level rise is unclear, albeit it is likely that they will in at least some cases erode and recede to some extent with sea-level rise (see Section 2.9). Other common shoreline types whose vulnerability remains unclassified include some wholly artificial shorelines (eg, Hobart Port area), and some rocky shorelines with low backshore profiles (e.g., in southwest Tasmania). Many of these latter are likely to be minimal vulnerability shores, however their low backshore profiles mean that some will be prone to increased storm surge flooding, hence they require assessment on a site-specific basis.

Other unclassified shores have unusual combinations of the geomorphic attributes encoded within the *tascoastgeo_v4gda* / *tascsthz_v2gda* datasets; many of these will probably require assessment of their vulnerability on a site-by-site case – specific basis.

Digital map file (shapefile): *tascsthz_v2gda* (GDA94 datum)
Attribute field: *Unclass*

Attributes:		Total length (km / %)*
Not an unclassified vulnerability shoreline (i.e., classified as having some indicative vulnerabilities, or as having minimal indicative vulnerability):	00	5427 km / 84%
Unclassified Vulnerability shoreline:	01	1045 km / 16%

Table 12: The extent of unclassified vulnerability shorelines on the Tasmanian coastline, as encoded in the *Unclass* attribute of the *tascsthz_v2gda* indicative coastal vulnerability map of Tasmania.

* Length at 1:25,000 map scale, including Bass Strait Islands, all other major islands, and most small islands, but not including Macquarie Island. Entire coastline length at this scale is 6472 km (slightly longer than the coastline length in the first edition of this mapping – *tascsthz* (Sharples 2004a) – due to subsequent addition of a number of coastal lagoons to the map). Percentage is the percentage of that total coastline length occupied by the specified shoreline type.

5.0 RECOMMENDATIONS

The production of this second edition of the Indicative Mapping of Tasmanian Coastal Vulnerability has implemented several of the recommendations for further work that were made in the first edition (Sharples 2004a). Remaining and additional recommendations arising from the indicative coastal vulnerability assessment of Tasmania described by this report are listed in dot point format below, and in most cases additional discussion is provided in the indicated sections of this report.

The indicative coastal vulnerability mapping provided with this report constitutes the logical first step in a broader strategic approach to coastal vulnerability assessment and management, as outlined in Section (3.0). Hence, the recommendations provided below are essentially aimed at progressing such a strategy to its subsequent logical stages:

Indicative (First Pass) Assessment:

- The indicative coastal vulnerability assessments provided with this report should be used as precautionary assessments of coastal vulnerability to guide coastal planning until such time as more detailed site-specific assessments are available for priority areas (see Section 3.2).

- The indicative mapping of shoreline erosion and recession vulnerabilities provided with this report (Sections 4.3.3, 4.3.4, 4.3.5 & 4.3.6) indicates shorelines potentially susceptible to these hazards, but provides no indication of how far to landwards such recession might proceed over (say) 50 to 100 year periods. Detailed site-specific assessments and modelling of likely shoreline recession distances are needed to make such forecasts (Section 3.3.2), however this has not yet been undertaken for any Tasmanian shores. Indeed, even when detailed assessment and modelling is undertaken, some degree of uncertainty will remain, and Cowell *et al.* (2006) advocate that this uncertainty be made transparent by quoting estimates of shoreline recession in terms of the probability of various degrees of change occurring.

  It is recommended that planners and policy-makers give consideration to the most appropriate means of defining precautionary recession vulnerability envelopes behind shorelines indicatively assessed as being vulnerable to erosion and recession (see discussion in Sections 2.3 & 4.3.3).

- Mineral Resources is continuing to undertake new geological mapping – some of it coastal areas – to identify geological substrates prone to slumping (landslides). As such mapping becomes available it should be used to update the *tascoastgeo* shoreline geomorphic map, which should in turn be used to upgrade the indicative mapping of slump-prone coasts provided by the *Erosvuln* attribute of the *tascsthz_v2gda* coastal vulnerability mapping (see Sections 2.7 & 4.3.5).

Regional (Second Pass) Indicative Assessments:

- The exposure, wave energy and sediment budget attributes in the *tascoastgeo_v4gda* and *tascsthz_v2gda* map datasets should be upgraded and reviewed as described in Appendix 3, and incorporated into regional ("second pass") indicative assessments of Tasmanian coastal vulnerability areas (see Section 3.3.1). These datasets could be used to build on the approach to "Second-Pass" assessment of Tasmanian coasts using a Coastal Vulnerability Index that has been initiated by Leaver (2005).

Site – Specific Assessments and Modelling:

- The indicative coastal vulnerability assessment provided with this report should be used, in combination with socio-economic data and trends, to identify indicative coastal vulnerability areas that are under significant pressure from development or use, and hence should be priorities for site-specific vulnerability assessments and modelling (see Section 3.3.2). Pilot studies should be undertaken at a range of such sites to determine the scale and scope of site specific investigations needed to improve understanding of the vulnerability of each site.

Shoreline Monitoring

- Programs to monitor the response of a range of Tasmanian shorelines to sea-level rise should be funded, encouraged and supported (see Section 3.4). Monitored shorelines should include high risk indicative coastal vulnerability zones that are under development pressure, relatively undisturbed beaches (as "benchmark" sites), and a broad representative range of shoreline types distributed around the Tasmanian coast.

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