Application of Geomorphic Frameworks to Sea-level Rise Impact Assessment

Prepared for Geoscience Australia

Matt Eliot
Damara WA Pty Ltd

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Executive Summary

This document describes potential application of geomorphic frameworks to the improved assessment of sea-level rise impacts. Assessment of coastal response to sea-level rise has demonstrated diversity that is beyond the capacity of widely used simple models to represent successfully. Use of increasingly conservative climate change scenarios to extend the use of these models to more complex coasts is ultimately an impractical solution, as the methods cannot distinguish relative sensitivity along the coast. This potentially leads to a breakdown of the principle of intelligent siting to avoid coastal hazards. Geomorphic frameworks are proposed as a robust means to facilitate an appropriate level of complexity in sea-level rise impact assessment.

The geomorphic framework acknowledges that coastal change occurs at every spatial and temporal scale, with active coastal processes influenced by geology, geomorphology and interaction with terrestrial hydrology. The approach uses geological and geomorphic information to identify scales, processes and their relationships, with which to describe projected coastal change. A hierarchical geomorphic framework is recommended, which allows capture of key processes that are active at different scales, cross-checking of feedback or inputs between scales and the use of sparse information that has been developed at different scales. The concept of shifting between scales through upscaling and downscaling is essential to help resolve differences that occur between local-scale engineering assessments and wider-scale geomorphic analyses.

The use of geomorphic frameworks has been demonstrated through development and application along the Western Australian coast, with focus on the southwest and northwest, as these areas have diverse morphology, yet both display compartmentalised behaviour. Landform analysis techniques used to identify geomorphic frameworks have been based on existing studies for: (i) sites for which small-scale or large-scale assessment has previously been undertaken; and (ii) sites where multiple scales of enabling information (geology, geomorphology, meteorologic and oceanographic analysis, sediment transport analyses, detailed bathymetry and seabed mapping) is available. A combination of generic description and site-specific examples is provided to demonstrate techniques for 'real-world' use of the frameworks across the wider Australian coast. The examples demonstrate how a hierarchical geomorphic framework, landform classification and mapping may be used to support planning of coastal land use or adaptation, policy and applications.

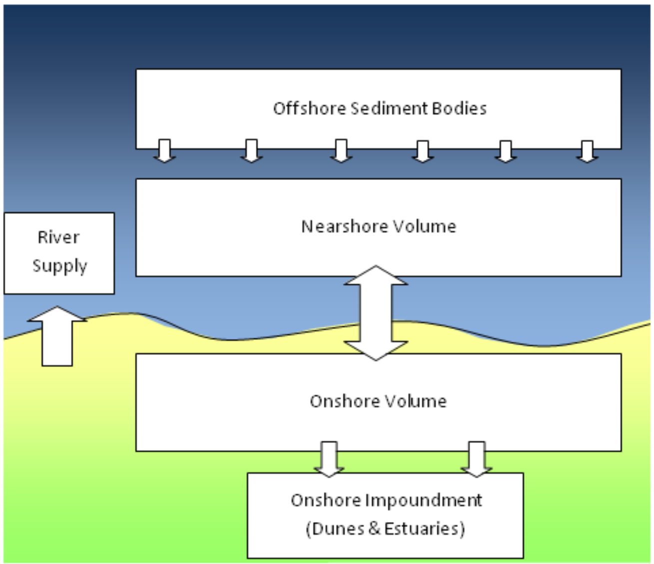
Landform assessment at multiple scales has suggested there is a relative transition of critical information from meteorological and oceanographic processes, through sedimentological information, towards coastal geology for increasingly large spatial units. This implies a multi-disciplinary approach is required for successful definition of geomorphic frameworks. In a similar manner, the coastal process cascade from storm response, through alongshore transport, to long-term coastal evolution needs to be considered when relating information developed at different scales.

Application of geomorphic frameworks to both the southwest and northwest coast of Australia have demonstrated the significant roles played by the geological framework, alongshore transport mechanisms and the energetics of shore—shelf sediment exchange. These dynamics have been summarised as behavioural models for coastal evolution, which demonstrate significant differences to the widely used coastal evolution model based on cross-shore exchange (see Figure below). Along the southwest, the role of nearshore rock reefs and coastal rock features are critical to compartmentalisation of the coast and its likely response to sea-level change. For the Pilbara, intermittent delivery of sediment from large rivers and the capacity for exchange between the coast and tidal flats are key differences to the more general behavioural model.

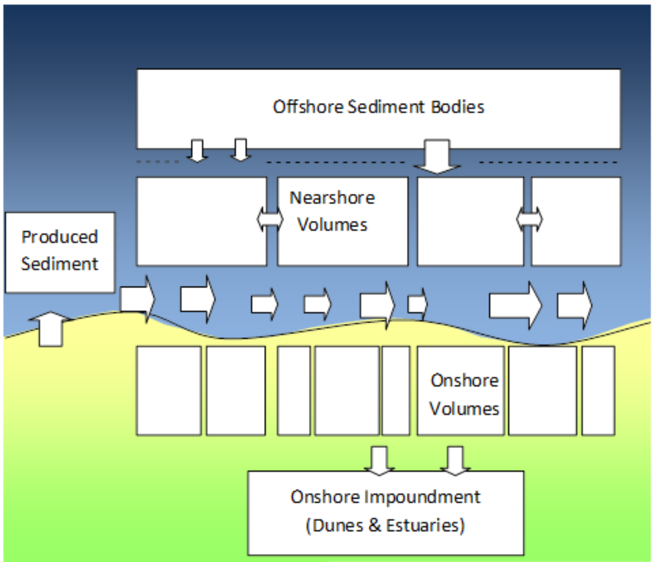
Improvements in the available technology and recent advances in coastal science have facilitated more efficient definition and use of geomorphic frameworks. A key advance in technology has been the reduced cost for collecting detailed bathymetry, including multi-beam hydrographic techniques or airborne depth sounding (LiDAR and LADS), which has provided significant improvement to landform analysis capacity. The most relevant advances in coastal science involve consideration of landform relationships, which may be used with geomorphic frameworks to more strategically identify the most likely pathways for coastal response to sea-level rise along the diverse Australian coast.

The greatest benefit likely to be provided by application of geomorphic frameworks is the capacity for improved transfer of information collected at different scales. This enables more efficient use of sparse knowledge, and greater ability to identify conflicts between studies at different scales. The transfer of information from larger scales to smaller scales is particularly important for decision-making at a local planning or engineering scales, including the selection of appropriate means of local adaptation to sea-level rise.

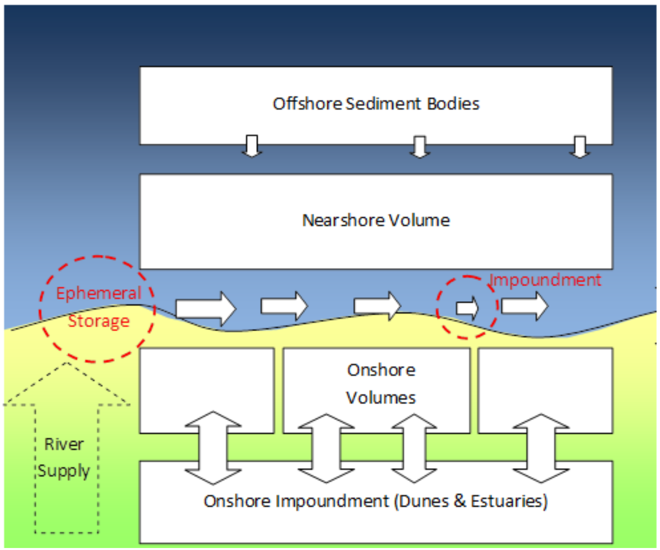
(a) General Behaviour Model based on cross-shore exchange



(b) Southwest WA Behaviour Model based on extensive nearshore reefs and coastal rock features



(c) Pilbara Behaviour Model based on intermittent river supply, alongshore transport and large shore-estuary sediment exchange



Behavioural Models Developed through Landform Analysis

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1. Introduction

Potential sea-level rise is a global challenge, with assessment of possible coastal impacts [1,2] and identification of adaptation pathways occurring at all levels of governance [3,4]. Geomorphic frameworks have been proposed as useful for relating assessments developed at different spatial and temporal scales [5]. A key philosophy behind the use of coastal geomorphic frameworks is the feedbacks between geomorphology, coastal mobility and dynamic coastal processes (see Appendix A). Correspondence between coastal change and coastal processes, albeit with some lags and distortions, is dependent on the geomorphic context. In this respect, it is considered that the frameworks may help refine coastal impact assessments, many of which are based upon simple conceptual models for response to sea-level rise [6,7,8]. This document provides a description of geomorphic frameworks and demonstration of how their application may improve sea-level rise impact assessment in Australia.

It is acknowledged that this document largely provides examples of geomorphic processes active over scales of hundreds of metres to tens of kilometres. This is a result of the relative availability of studies at these scales. The limited number of larger-scale examples reflects the need to develop an improved understanding of larger-scale morphology and response to sea-level rise. Geomorphic frameworks are proposed as a fundamental means to describe relationships between these scales, and facilitate improved representation of coastal response to sea-level rise.

1.1. Background

Coastal response to sea-level variation has long been recognised for its occurrence over geological time scales, with its role in coastal management first recognised on subsiding coasts [9,10,11]. Its importance to coastal management investigations was extended by recognition of decadal scale sea-level phenomena [12]. Sea-level induced coastal change was given greater immediacy and its global importance highlighted in the 1980s through identification of relationships between greenhouse gas emissions and mean sea-level [13]. Advancing science regarding this relationship was paralleled by impact assessments for different parts of the coast and consequent policy refinement in Western Australia [14,15]. A general shift towards adaptive coastal management frameworks has occurred, placing strain upon existing planning structures, which in many instances are built with an assumption of long-term reliance upon inflexible management boundaries. The resulting range of information sources and varying treatment by agencies with disparate responsibilities produced a complex situation, mixing site-specific and more general studies, each with different biases. This made it difficult to synthesise this information into an assessment of potential sea-level rise impacts across Australia, or even within each state.

Through the Coalition of Australian Governments (COAG), there was a concerted effort between 2005 and 2009 to develop a more consistent Australia-wide coastal information base relevant to assessment of sea-level rise impacts. This information was summarised in *Climate Change Risks to Australia's Coast* [16], a large-scale assessment which has provided the basis for a number of smaller-scale sea-level rise impact assessments, ranging from regional through to very local. A key difference to the complex situation preceding the Australia-wide report is that reference to the broad-scale assessment and its range of scenarios allows more direct comparison between discrete studies.

The contribution of *Climate Change Risks to Australia's Coast* [16] to coherence between discrete assessments provides a direct parallel to the main benefit of incorporating geomorphic frameworks in sea-level rise impact assessments. Specifically, the frameworks may support upscaling or downscaling of coastal change assessment [17]. This has been applied both qualitatively to landform-based vulnerability assessment [18,19,20,21,22] and quantitatively to estimates of erosion due to sea-level rise [23,24,25]. In the latter case, upscaling involves aggregating sediment transport rates and volumes to a larger scale, while downscaling involves additional knowledge to estimate how the overall pattern of accretion or erosion will be distributed at a finer scale.

The capacity for improved assessment of coastal change through the use of geomorphic frameworks reflects a tension between coastal science and policy, where the complexity identified by science requires simplification to facilitate inclusion in policy. Reviews of Australian coastal zone policy have identified a convergence of approaches, particularly towards the use of coastal setback allowances, typically using variants of the method for sandy coasts [26,27]. This method captures a simplified set of coastal processes and therefore presents systematically biased results in the estimation of change according to how well active processes are represented. The result is arguably reflected in the National Coastal Vulnerability Assessment project [28], where high risk sites corresponded to a limited range of coastal morphologies [6].

The need for wider representation of coastal morphologies has been reflected in recent progress of international coastal change assessment practices [29]. At the simplest level, regional differences between coastal type (e.g. barrier dunes, floodplain, headland controlled or cliffed) require consideration when choosing assessment methodologies [30]. More complex application of morphology has involved defining relationships between adjacent landforms. This has included conceptual models such as estuary–coast interaction [31], or more highly resolved mapping of connections between landform elements and their associated sediment exchanges [32,33].

Recent research on the United States' east coast has indicated the role of inner-shelf geology in the location of erosional 'hotspots' along the shore, and its effect on terrestrial landform development by providing a fixed framework for coastal processes [34,35]. Such an understanding is also paramount for much of the mixed sand and rock shores of Australia's coast, as demonstrated by application of water penetrating LiDAR to the inner continental shelf and nearshore waters of both southwest Australia and the Pilbara (see Section 6).

Techniques recognising the effects of different morphologies within the assessment of coastal response to sea-level rise have been robustly debated [31,36]. Although a number of alternate approaches to estimate coastal response to sea-level rise have been established [37], these are not widely used. One single technique is predominantly used, despite the author identifying its limited applicability [38]. Typical reasons for this include convenience, simplicity, precedence in policy or insufficient evidence available to define an alternate pathway. In contrast to this position, landform mapping and interpretation of late Holocene features strongly suggest geomorphic response to sea-level change is far from uniform. It indicates there may be considerable benefits to incorporating geomorphic frameworks, specifically because of landform connectivity, into assessment of potential coastal change.

1.2. Coastal Landform Analysis

Landform analysis is an integral part of coastal change assessment. It has been fundamental to the development and progression of coastal modelling, although its role is becoming increasingly obscured through the parameterisation of landform characteristics, particularly gradients and bed roughness. Significant recent advances in both the science [32] and technology [39,40] of landform analysis have provided opportunity for its improved use, including airborne and remote-sensed depth measurements through LiDAR and LADS. Further, the divergence of coastal modelling from its previous roots in landform analysis may facilitate the use of landform information as an independent support to modelling, through process identification or model verification (see Appendix A).

There is a strong relationship between coastal landforms, the materials that comprise them and the environmental forcings that shape them [41]. Consequently, a description of any of these three elements may explain much of the observed coastal geomorphology. The effectiveness of analysis focused on each individual element enables their use as partly independent primary tools for the approaches of coastal geology (and sedimentology), geomorphology and hydrodynamics. Technique selection when analysing a coastal system is often determined by information constraints: either available data or the practitioner's knowledge. However, systems analysis should generally be undertaken with focus on the element that best explains observed variability, with all three represented. In general, this is a scale-dependent progression, with geology or sedimentology most applicable at coarse scales and hydrodynamics most applicable at fine scales, although advancements in numerical methods in recent decades has seen increased application of hydrodynamics to larger scales.

Analysis of coastal land systems and landforms focuses on the identification of landform characteristics as a means of determining likely dynamic behaviour in response to imposed change. The approach is necessarily cognisant of sedimentology, lithology and hydrodynamics, but fundamentally assumes that the morphology is more influential upon coastal change than other factors. A simple example of this behaviour is the increasing potential scales of coastal change due to sea-level rise for a beach actively supplied by river sediments, one controlled by headlands, an open coast beach or a low-lying barrier system.

In its most widely used application, which is to support numerical modelling, landform analysis involves identification of landforms and description of materials. However, the value of landform analysis may be significantly advanced through the use of a hierarchical geomorphic framework. When built around the concept of connectivity, or its counterpoint of compartmentalisation, the approach provides opportunity for multi-disciplinary use of the most scale-critical information; with potential for upscaling and downscaling as a means of more effectively using sparse coastal data.

1.3. Complexity of Sea-level Rise Impacts

A key challenge faced by sea-level rise impact assessment is the complexity of landform response to sea-level rise. In addition to differences between coastal materials (mud, sand, gravel or rock) and differences between coastal landform types (e.g. reefs, beaches, cliffs, estuaries), there are also considerable landform interactions. These may occur between adjacent landforms or be the relationship of larger landforms to smaller landforms from which they are comprised. The result of complex landform response is that for any representation of change, there will be misrepresentations of a similar scale to the projection.

Commonly, simple methods of assessing coastal response to sea-level rise are applied that are intended to be conservative in scope, such as defining a constant (say 100m) setback allowance [42]. A major problem of simple approaches is that relative coastal sensitivity is not distinguished, and hence there is underestimate of hazard at sensitive sites and overestimate of hazard at more stable locations. Application of greater conservatism reduces under-estimated responses, but correspondingly increases the over-estimated response. Hence, the more conservative the approach, the larger the challenge posed by sea-level rise appears to be.

There is an opportunity for increased assessment complexity to significantly clarify the scope of the challenge posed by sea-level rise. This includes improved targeting of areas that are sensitive to change, potential for identification of smaller scales of adaptive response and greater use of more stable coastal locations.

Geomorphic frameworks offer a potential approach towards increasing assessment complexity, so as to achieve a better representation of likely coastal change. The use of a hierarchical framework, as proposed in this document, provides a systematic means of identifying and scaling the required level of complexity.

1.4. Australian Context

The nature, scale and distribution of sedimentary coastal landforms around Australia provides indication of how the coast is likely to respond to sea-level rise, the key processes and the degree of complexity required to project change. Previous classifications of estuarine and beach morphology have considered influences from weather systems, oceanographic processes, terrigeneous input, chemical and biological processes [43,44,45]. In addition to these influences, the relative volume within coastal barriers suggests variation in the supply and retention of sediment along the Australian coast, which has been clustered into three sedimentological provinces and 17 sub-provinces [46]. Different supply rates between the temperate and tropical regions suggest that some spatial variation may be attributed to the weather and oceanographic processes driving landform development. However, the considerable variation within these regions suggests additional factors are active, including the capacity for enhanced sediment retention and landward transfer due to nearshore reefs and rock platforms [47].

A possible further cause of variation is suggested by the relative sea-level sequence over the late Holocene, with almost 85% of the Australian coast experiencing a highstand at some stage between 6,000 and 3,000 years before present, the exception being Tasmania and the southeast mainland [48,49]. For those locations experiencing highstand, subsequent decline of sea-level may provide opportunity for increased shelf—shore transfer [50].

Broad clustering of morphology and sediment availability suggests that key characteristics likely to influence coastal response to sea-level rise are:

- Weather and oceanographic processes driving coastal landform development, which therefore determine landform and seabed connectivity;
- The presence of geological structures capable of sediment retention; and
- Ongoing supply of sediment from marine or terrestrial sources, which includes both of the above factors and possibly the effect of relative sea-level on shelf—shore transfer.

These characteristics vary around the Australian coast, and are strongly related to the previously defined sedimentological sub-provinces [46]. Landform analyses conducted for the western Australian coast suggest that variation of geological structures is likely to imply a finer classification scheme [5].

1.5. Focus of this Document

This document has been prepared to provide demonstration of potential applications of geomorphic frameworks to the assessment of coastal impacts of sea-level rise. A combination of generic description with site-specific examples is provided, to facilitate 'real-world' use across the wider Australian coast. However, due to the significant development and application of hierarchical frameworks to the Western Australian coast, along with the author's professional focus, there is a geographic bias towards the Vlamingh (Cape Naturaliste to Mandurah) and Pilbara (Onslow to Port Hedland) Regions (see Figure 1).

Although both Vlamingh and Pilbara have largely carbonate coasts and have evident partitioning, the two Regions are starkly different with respect to the key characteristics likely to influence coastal response to sea-level rise (see Section 1.4). The Vlamingh Region is micro-tidal, experiences temperate conditions, has significant nearshore geological structures providing shelter, has low supply of terrigeneous sediment, and has retained a very large quantity of sediment in coastal barriers over the late Holocene [46]. In contrast, the Pilbara Region is mainly macro-tidal, experiences arid-tropical conditions including tropical-cyclone impact, has a high supply of terrigeneous sediment and has captured little sediment in coastal barriers over the late Holocene [46]. Contrasts between the two Regions therefore help display the range of concepts necessary to consider when developing and applying geomorphic frameworks for the wider Australian coast.

Techniques for use of geomorphic frameworks have been demonstrated using: (i) available information; (ii) sites for which small-scale or large-scale assessment has previously been undertaken; and (iii) sites where multiple scales of enabling information (geology, geomorphology, meteorologic and oceanographic analysis, sediment transport analyses, LiDAR/LADS bathymetry and seabed mapping) is available. The examples demonstrate how the coastal partition hierarchy, landform classification and mapping may be used to support coastal land-use or adaptation planning, policy and applications.

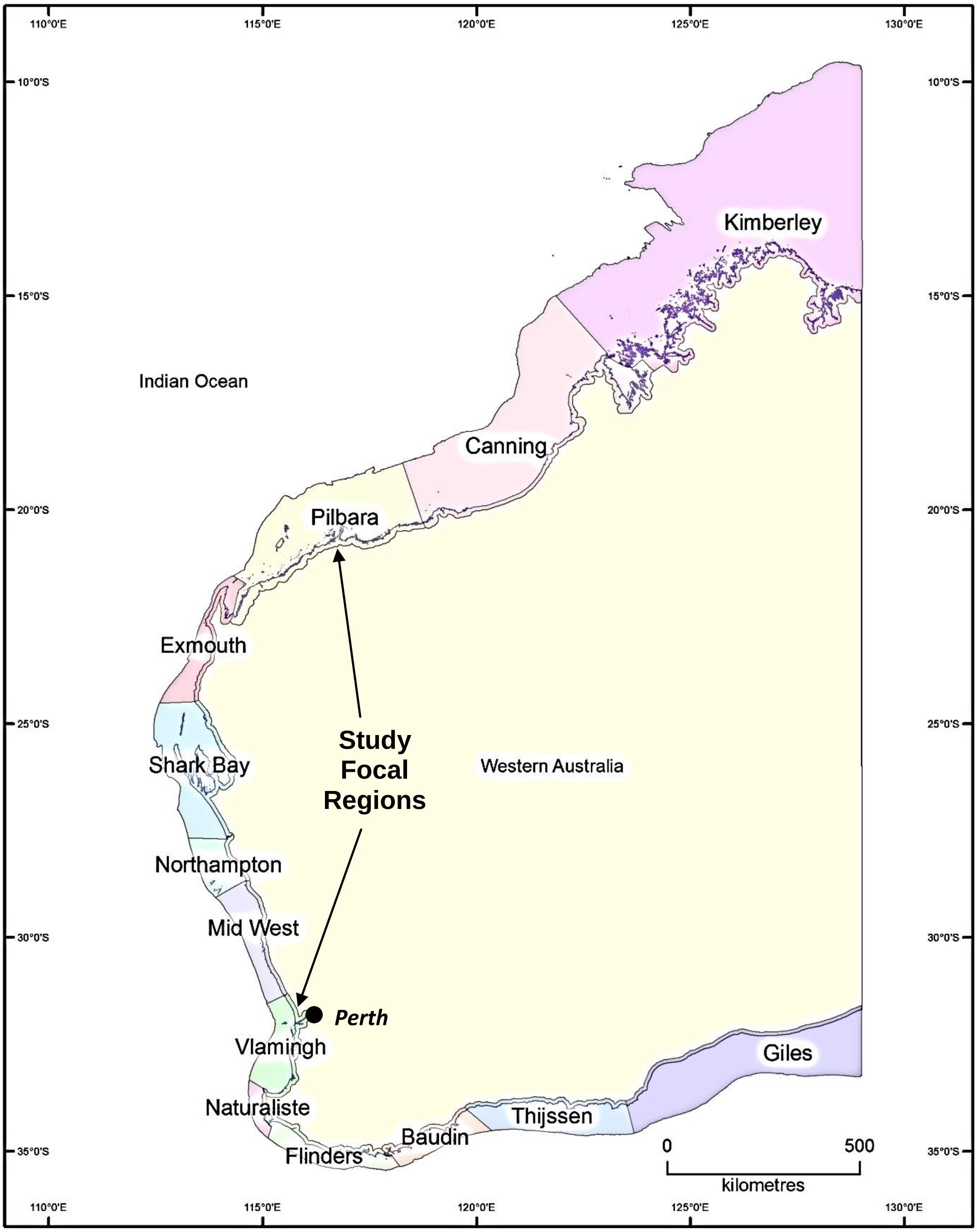


Figure 1: Western Australian Coastal Regions
Figure prepared by GSWA after Eliot *et al*. (2011) [5]

2. Geomorphic Frameworks

In the context of coastal change assessment, a geomorphic framework uses geological and geomorphic information to define spatial and temporal limits within which we describe patterns of observed or projected change. Behavioural similarity or spatial connectivity, due to sediment transfers, potentially provide basis for clustering. Increased tolerance of variability allows greater clustering and therefore enables definition of coastal compartments definition at any scale of coastal management. It is recognised that the type of information needed and its precision are likely to change with scale.

Selection of any single scale for assessment of coastal change defines (1) the key process-response characteristics; (2) the smallest scale of local features that can be resolved by the assessment; and (3) external factors that are not subject to the imposed change (see Figure 2a). For every different morphology or scale, a different suite of process-response characteristics is active. Application to each assessment results in a different domain which gives precise results, with consequent implications for the management tools required for decision-making (see Figure 2b). For example, high precision is required at infrastructure scale, where the need to distinguish between sea-level response and decadal cycles of erosion-recovery may be crucial when evaluating whether to adapt a coastal structure or retreat; while lower precision forecasts may be suitable for land-use planning.

Different approaches to balancing the assessment scale and the domain of precision define alternative geomorphic frameworks (see Figure 2c to 2e). Multiple process-response relationships may be developed for different morphologies, such as distinguishing between beaches, barrier coast, wetlands, estuaries and cliffs [29,30]. This allows use of a single spatial scale, and allows precision at any point to be improved through more refined classification of morphology (Figure 2c).

Generic systems, including numerical modelling, are capable of simultaneously representing a broad range of conditions and processes. Applicability can be refined through the use of finer scale representation, or additional active processes (Figure 2d). The amount of effort required may dramatically increase for capture of fine scale and multiple processes.

Hierarchical assessment uses larger scales to inform smaller scales, with focus at each scale targeted to provide the overall required level of precision (Figure 2e). This approach includes nested numerical modelling, although a hierarchical framework can also be used for conceptual or analytic models. This document focuses on use of hierarchical geomorphic frameworks.

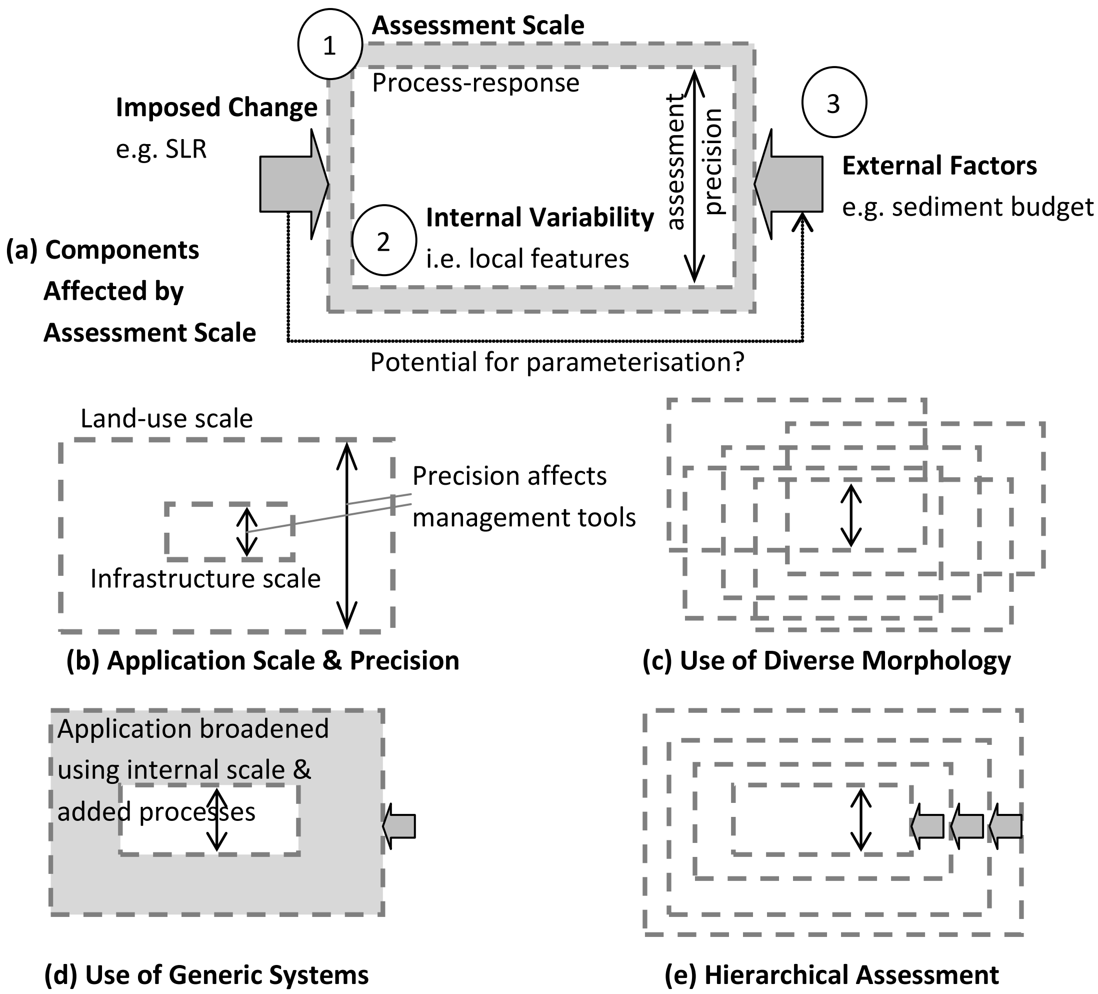


Figure 2: Approaches to Geomorphic Framework Definition

2.1. Coastal Compartmentalisation and Connectivity

Definition of internal spatial scales within a geomorphic framework requires consideration of the intended application and the required degree of precision that results from the combination of available information, process-response relationships and the scale of representation. Globally, there are examples of coastal compartmentalisation being applied at all scales ranging from the continental scale down to local embayment scales. The diversity of this extensive scientific base and the difficulty of transferring between applications suggest a need to vary the basis for compartmentalisation according to regional morphology and scale.

Recent applications of coastal compartments in the United States of America [51,52], United Kingdom [53] and Europe [54] have recognised scale dependencies, and have generally converged towards the use of coastal compartments based upon connectivity, although at scales that are varied to suit management purposes. On this basis, sections of coast for which coastal response is strongly related due to sediment transfer are defined as cells, compartments or tracts according to terminology and scale. In general, boundaries between these sections are associated with reduced transfer. Hence the concepts of connectivity and coastal compartments are strongly linked.

Definition of coastal sediment cells is often paired with the definition of coastal sediment budgets. However, while sediment budgets are a useful tool to help describe connectivity and are most appropriately defined in the context of sediment cells, they are not intrinsic to defining coastal compartments.

A key advantage of linking coastal compartments to connectivity is the improved ability for scale transfer, through upscaling and downscaling (see Section 5), when using a hierarchical coastal frameworks (see Section 2.2). This provides a holistic perspective of the areas being evaluated and may significantly enhance the capacity to use sparse coastal data.

2.2. Hierarchical Frameworks

The concept of coastal compartments has been incorporated into different types of coastal management at many scales. While economic or jurisdictional boundaries occur frequently, issues that cross boundaries or cover multiple coastal compartments may become problematic for coastal management. Instead, it may be preferential to define sections of coast within which coastal management issues of interest remain largely discrete. Such an intent prompted the use of 'natural boundaries' in environmental management, stemming from catchment management [55,56]. Extension of the natural boundary concept to the coast occurred for locations where modification of river systems affects sediment supply, subsequently viewed as a useful framework for coastal management [57]. The concept extends further offshore within the framework of integrated coastal zone management [58]. In the United Kingdom, shoreline management plans are directly related to coastal compartments, termed coastal management units [53].

Coastal compartments using natural boundaries is used on national scales of coastal management in the United States and the United Kingdom[59,60]. Major river systems were used for compartmentalisation along the United States' western seaboard, with management divided into littoral cells in the order of 100km length [61,62] between which sediment exchange is considered to be limited. A similar approach was undertaken within the United Kingdom, with smaller coastal management units based on constraints to sediment transport along the coast [63,64], and less emphasis upon riverine sediment sources.

Definition of coastal compartments using natural boundaries has previously been undertaken for Australia for the purposes of marine natural resource management [65]. However, identification of compartments for coastal management purposes has only been undertaken for a relatively small proportion of the Australian coast [66,67,68,69]. A major reason for this is jurisdictional, as state and local government agencies are principally responsible for coastal management, and therefore use smaller management scales that are not generally conducive to looking at larger scales. The limited use of coastal management compartments is also because needs change geographically, limiting justification of any single-scaled spatial framework across Australia, as different scales are appropriate for different management purposes or morphology. The notion that a hierarchy of coastal compartments and sediment cells, based on a consistent application of a geologic framework and morphologic criteria, might have application to different levels of coastal management jurisdiction and practice is comparatively new.

A further challenge to the definition of coastal compartments is that coastal processes are fractal in nature, with many different related scales [70,71,72]. Consequently, while all processes are active at all scales, some dominate the apparent process-response for each particular scale. The tendency for a single defined scale to be used for assessment of processes is common, with concerted effort required to identify and link processes active at all scales [73]. This may be addressed by hierarchical classifications of morphology, such as the logarithmic scale progression of Schwartz [74]. However, a purely scale-based approach (e.g. dividing a coast into even segments) potentially provides results that change with small boundary movements and implies clustering of smaller coastal units regardless of their degree of association.

A hierarchical system for coastal compartmentalisation has recently been proposed for planning and coastal management in Western Australia [5] (see Figure 3). This framework was developed in conjunction with larger scales for marine planning, recognising that compartments at different scales are useful for different forms of management. Implications of varying morphology have been included through some changes to the basis of compartments, according to larger scale characterisation. In particular, a transition from geology to geomorphology as a basis for natural boundaries was identified when shifting from largest to small scales. Compartment hierarchies were developed according to relative degrees of connectivity, with interpretation of coastal landforms [75,76,77,78,79] providing significant supporting information. A key objective of the hierarchy is to provide the ability to upscale or downscale comparatively sparse coastal management information.

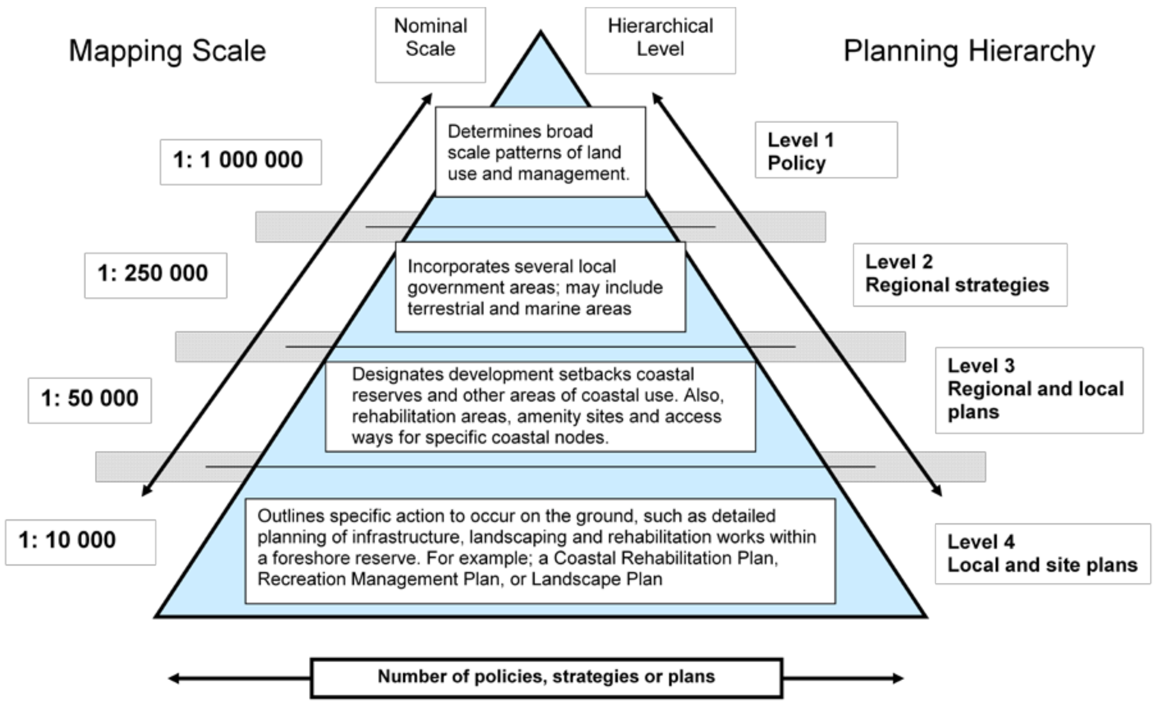
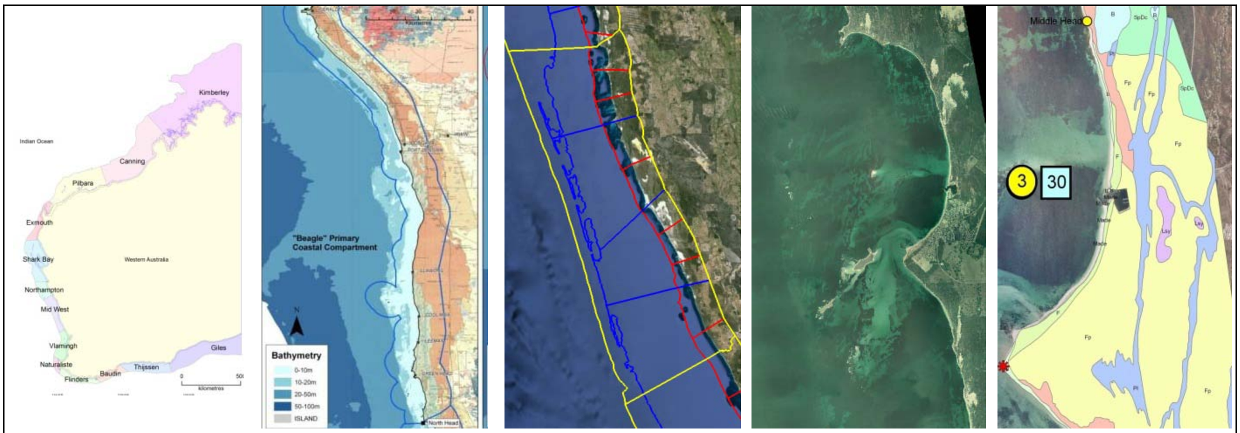


Figure 3: Planning Hierarchy Spatial Scales and Level of Information
Extract from Eliot *et al.* (2011) [5], based on WAPC (2013) [80]. The shape indicates the increasing number of plans required at more detailed scales for a single region, from policy to site level.

Terminology for coastal hierarchies varies between locations, with the terms used in this document based on those recently developed for the Western Australian government (see Figure 4) [5]. The hierarchical framework distinguishes between coastal compartments, which are essentially determined by geology, and sediment cells, which are determined by the connectivity of mobile sedimentary features and usually defined at smaller scales than compartments. Both compartments and sediment cells have a range of scales within them, which have been simply classified as primary, secondary or tertiary according to relative spatial and temporal scales. Generally, below the scale of sediment cells are landforms, with consideration of land systems, landform assemblages, landform units and landform elements representing aggregated through to constituent parts [56].



Regions: Areas with recurring patterns of landform and geology suitable for regional mapping at scales of approximately 1:250,000	**Land Systems:** Areas of characteristic landform patterns suitable for mapping at regional scales of 1:100,000 to 1:250,000.	**Compartments:** A local unit based on one or more landforms suitable for mapping at scales of 1:50,000 to 1:100,000	**Sediment Cells:** A local unit based several linked landforms suitable for mapping at scales of about 1:25,000 to 1:50,000	**Landforms:** A local unit based on one or more definite landforms suitable for mapping at scales of about 1:10,000 to 1:25,000

Figure 4: Hierarchical Coastal Scales
Proposed by Eliot *et al*. (2011) [5]

In loose terms, the compartments suggest the methodologies suitable for assessment of coastal change, the sediment cells define the spatial scale of the assessment, and landforms provide the building blocks within which sediment exchange may occur. Evaluation of coastal response to sea-level rise most commonly faces issues of upscaling or downscaling around a sediment cell scale (see Section 5), due to the role sediment budgets play for local-scale planning or engineering assessments.

In the Australian context, there is a relative lack of information and assessment at the compartment scale, although there is recognition that larger scale information may define external conditions for smaller scales (see Figure 2). Without such information, a sediment budget requires assumption of a net balanced area, i.e. a closed system. However, sediment cells need not be wholly closed coastal units, and it is often the relative exchange between cells that determines the distribution of erosive pressures.

3. Sea-level Rise and Coastal Impacts

3.1. Coastal Response to Sea-level Rise

The relationship between relative sea-level and coastal position has long been recognised, particularly on subsiding coasts. However, by the 1950s, the process had not generally been incorporated into commonly applied coastal modelling practice, largely due to the belief that its timescale was too gradual. Extension of the timescales of interest prompted the need to include variation of onshore sediment volume, which could not be adequately explained by alongshore transport modelling due to its assumption of mass conservation.

Significant extension to the alongshore modelling framework was made through development of a simple conceptual model by Bruun [81] (see Figure 5). The model applied wave-controlled equilibrium profiles to consider a volumetric balance between the inner-shelf and coastal margin. The relative elegance of the model and its ease of application have determined that it remains a preferred conceptual model of choice, despite commentaries regarding its limitations [82,83,84], including a detailed discussion by its original architect [38,85]. In the context of geomorphic frameworks, the most significant known limitation is for coasts with potential alongshore transport that varies spatially (e.g. irregular wave shelter or shore alignment). This is a characteristic common to slowly evolving coasts, those with relict features, or coasts with significant anthropogenic influence. However, the Bruun model validity may also be constrained by morphology, including tide-dominated coasts [86], mixed rock-sand coasts [87] and island or dune barrier coasts [88].

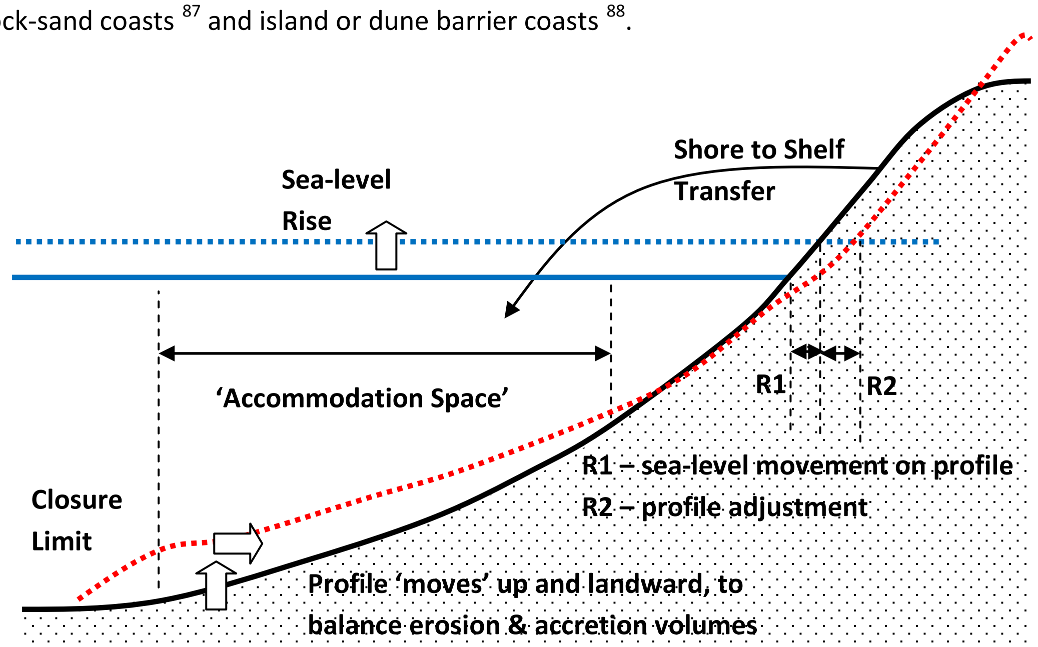


Figure 5: Concept of Shore–Shelf Exchange used for Bruun Model

Manipulations and extensions of the Bruun model were undertaken to broaden its applicability [89,90]. These have generally preserved the cross-shore nature of the model, but rarely acknowledged its need to be integrated with an assessment of alongshore transport [85]. It is consequently implicit that the model is most applicable at larger scales, with validation requiring spatial aggregation [91] and estimation of inputs and losses (see Figure 6). The need for careful interpretation of information from different scales has been acknowledged [92], with the concepts of timescale dilation[a] and net zero-sum behaviour[b] commonly used as convenient tools for geomorphic modelling.

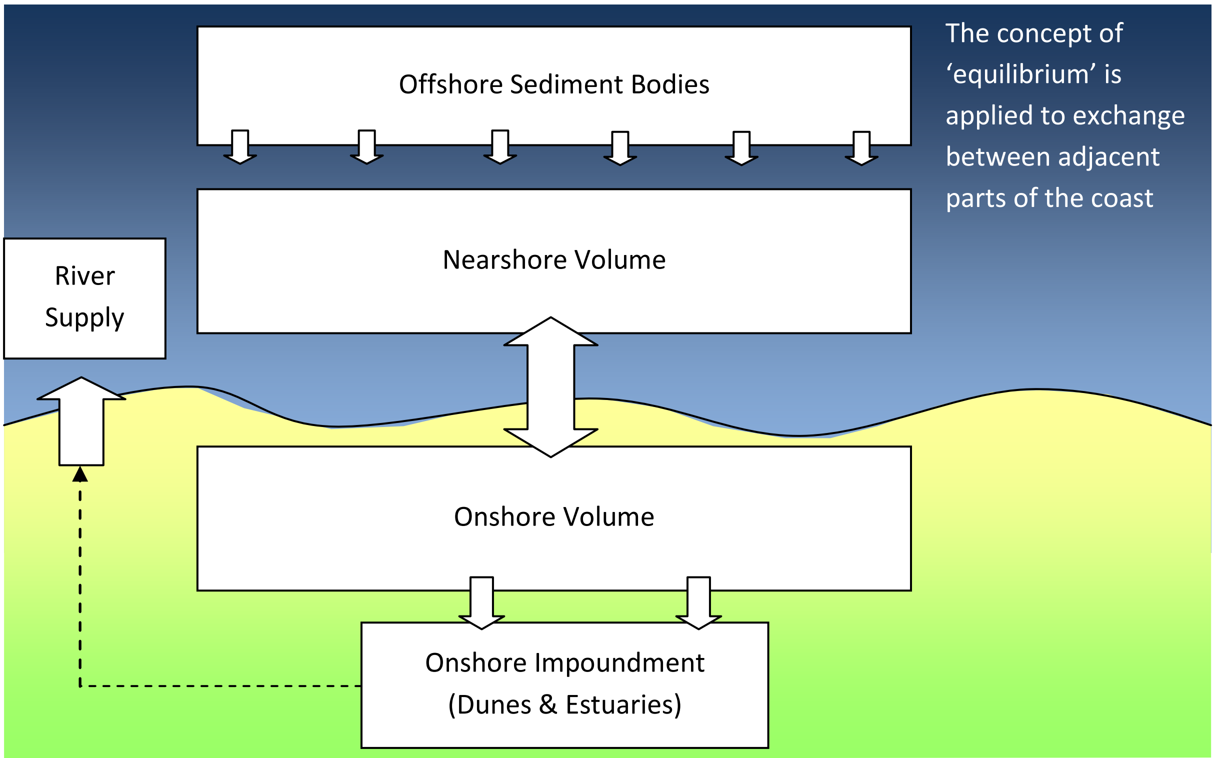


Figure 6: Schematic Behavioural Model with Cross-shore Balance

Cross-shore mechanisms for coastal response other than the Bruun model have been postulated such as nearshore bar or terrace growth, landward transfer of sediments or estuarine basin infill [82,93,94]. These mechanisms are based upon contemporary morphodynamics and stratigraphic evidence [95,96,97,98]. Representation of these mechanisms typical uses a similar conceptual approach to the Bruun model: considering connectivity of adjacent landform units, such as dune–beach [99] or coast–estuary interactions (Figure 7). A more detailed conceptual system for identifying and describing landform connectivity has been developed in the United Kingdom [32], following integration of analytic models for individual landform units [100]. The mechanism of estuarine basin infill deserves particular note, due to the potential interaction of wave and tide-driven sediment transport [94]. For estuaries or tidal channel networks with restricted entrances and low rates of fluvial sediment supply, sea-level rise may result in basin drowning, as evidenced by late Holocene evolution of the Pilbara coast [101].

[a] Timescale dilation is a convenient technique to describe the effect that timescales have upon the perception of net sediment transport. Shorter timescales are capable of displaying higher rates of transport, which reduce over longer timescales as oscillatory motions are smoothed out.
[b] Net zero-sum is a commonly applied assumption when modelling conditions of oscillatory transport. Use of this assumption is often a convenient means of simplifying model processes.

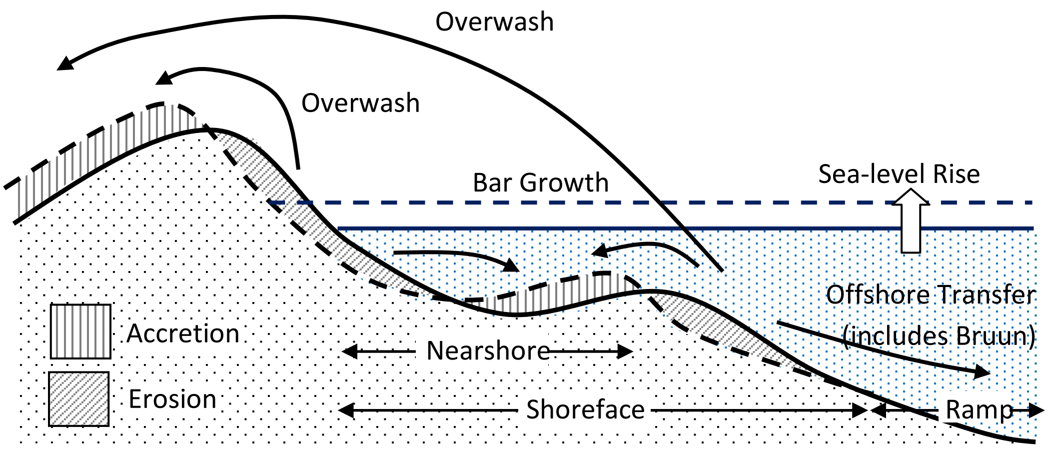


Figure 7: Cross-shore Response to Sea-level Rise
Modified from Dubois (1992) [82]

Implications of restricted landform connectivity are relevant to both alongshore and cross-shore coastal response to sea-level rise. Hence, when appropriately defined, geomorphic frameworks may identify both the predominant coastal landforms susceptible to sea-level rise and restrictions to transport. In this context, the proposed hierarchical framework incorporating coastal compartments and sediment cells may provide a valuable tool in the projection of coastal evolution.

3.2. Implication of Generic Climate Change Impact Frameworks

Approaches to sea-level rise impact assessment commonly follow generic climate change impact frameworks [102,103,104]. These frameworks are relatively structured despite the recent science underlying contemporary climate change (see Figure 8). This reduces the amount of effort required to interpret the complexities of climate change projection from a global to a local scale [105,106,107], and it has increasingly facilitated adoption of climate change scenarios within coastal planning and management [27,108,109].

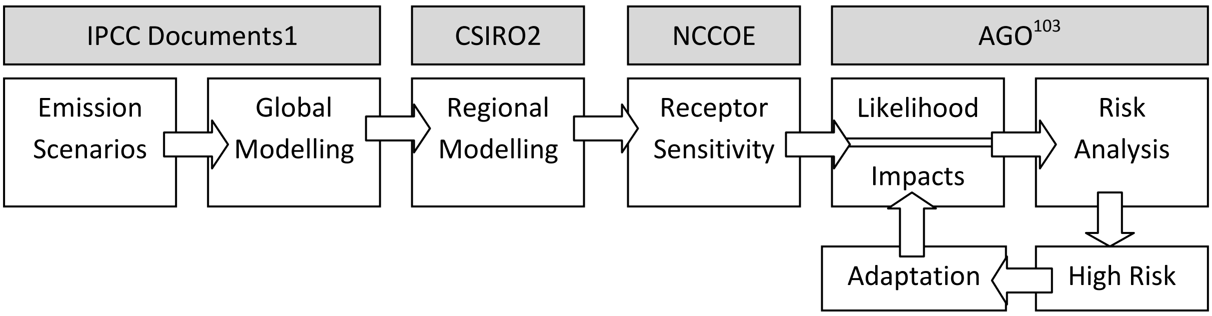


Figure 8: General Form of Coastal Climate Change Risk Assessments

A major limitation to the use of climate change impact frameworks is the constraint imposed by high levels of uncertainty, both with respect to projected change, and the corresponding environmental response. This encourages the use of simple analysis techniques, using adaptive frameworks within conservatively defined bounds. However, as discussed is Section 1.3, applications of fixed allowances or simple models for coastal recession lack discrimination, and become worse predictors of change with increased conservatism. Instead, application of conservative (high) climate change scenarios to a more complete process-based assessment may give a better means of tolerating uncertainty.

Selection of whether a conservative scenario is appropriate to sea-level rise impact assessment is strongly determined by the ultimate study end-use. The use may be broadly separated into three categories, which may affect the assessment approach:

1. Relative site sensitivity assessment;
2. Land-use planning; or
3. Adaptation planning.

These have progressively diminishing space and timescales as well as an increased requirement for precision. As discussed above, application of conservative (high) climate change scenarios to a process-based impact assessment may be an appropriate for indicative assessment of site sensitivity to compare geographic locations. However, the implications of timing and adequacy of proposed responses generally require both realistic (moderate) and conservative (high) climate change scenarios when developing adaptation plans (see Figure 9). Use of multiple scenarios with associated probabilities is recommended within generic risk-based impact assessment frameworks for assessment of options; however, this need may be offset in adaptation planning, where actions are based upon monitoring and triggers which can accommodate a progressive sea-level rise with only limited regard for likelihood.

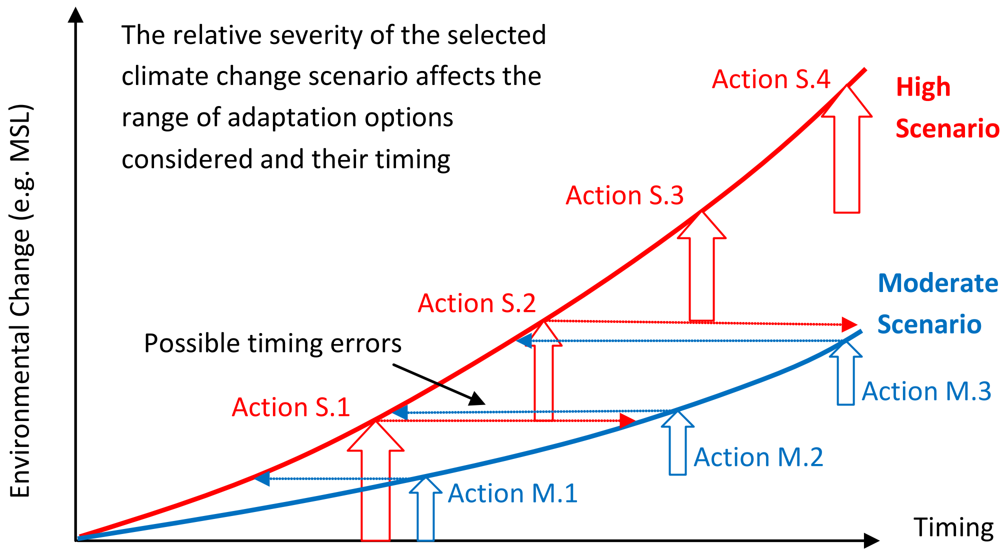


Figure 9: Effect of Scenario Selection upon Identified Adaptation Sequence

When either likelihood or timing is an important parameter, separation of the climate change response from natural coastal variability may under-represent the capacity for coastal change. The need for incorporating coastal variability into projections is significantly enhanced if the variability is a similar order of magnitude or larger than the response to climate change.

An alternative approach to the probabilistic methods suggested by generic frameworks for climate change impact assessment is the application of uncertainty-based analysis [110]. This approach incorporates uncertainty of process into the evaluation of possible outcomes, thereby highlighting the relative sensitivity to knowns and unknowns. The significance of this approach is amplified in this document because the uncertainty-based approach was applied on a regional scale to southwest Western Australia[111] and has been used here to aid description of relationships between regional and local scale assessments of coastal change.

4. Coastal Processes, Modelling and Scales

4.1. The Coastal Process Cascade

Coastal change occurs at every spatial and temporal scale, with active coastal processes influenced by geology, geomorphology and interaction with terrestrial hydrology [70]. This produces a process cascade in which for any given study scale, finer scale processes require aggregation [71], and coarser scale processes require consideration as extrinsic conditions (see Figure 10). Relationships between different assessment techniques may therefore be identified by the manner in which process information is aggregated or applied as an external forcing.

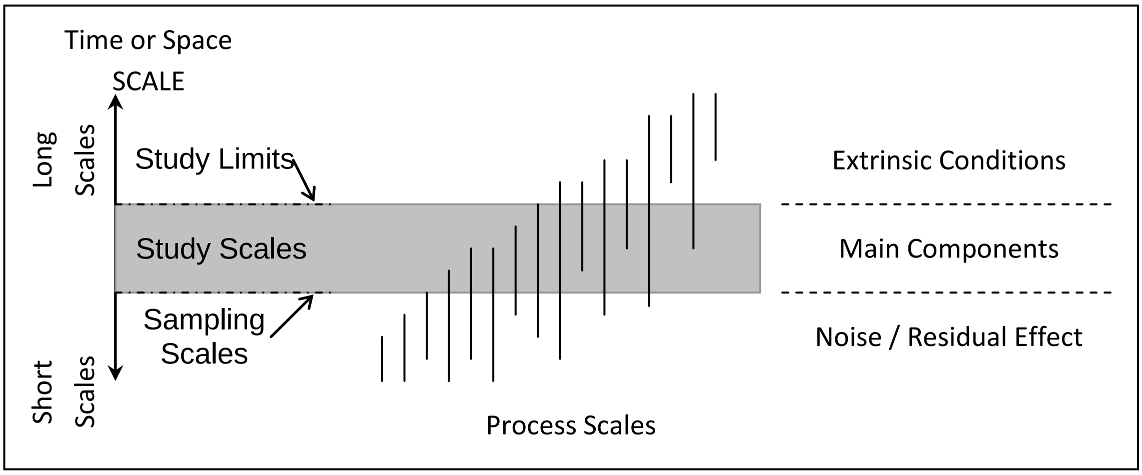


Figure 10: Relationship of Study Scales to the Process Scale Cascade
Modified from de Vriend *et al*. (1993) [92]

In principle, different levels of the coastal hierarchy may more strongly describe various aspects of coastal process-response. At the largest scale, compartments typically indicate how response models, conceptual or otherwise, should vary; intermediate scales imply the critical processes and connectivity; and at small scales the contributing elements and scales of the response model are clearly defined.

The importance of timescale assumptions has been highlighted on the southwest Western Australian coast through attempts to combine the Bruun model (see Figure 5) with observed and interpreted behaviour [25,111,112]. Patterns of erosion in response to sea-level rise over the twentieth century, and the apparent coastal dynamics over the late Holocene are not consistent with the conceptual model, particularly as rise up to 6000 years before present was associated with a large influx of sediment. The concept of timescale dependent dilation of the effective accommodation space (e.g. time dependence of closure depth in the Bruun model [90]) has been used in part to argue why there is such a significant difference in behaviour. However, interpretation of landform stability also suggests the efficiency of shore–shelf transfer is important, particularly on reef-sheltered or perched beach systems prevalent along the Western Australian coast.

Importantly, the time dependence of process scales also determines the type of information required to provide validation of processes. Coastal monitoring techniques typically provide information only about short- to medium-term processes, with geomorphic or stratigraphic information required to obtain evidence of longer-term changes.

4.2. Geomorphic Feedbacks and Scale-effects

A crucial consequence of the coastal process cascade is a parallel sequence (in size) of geomorphic features, ranging from coastal compartment scale down to micro-scale features such as ripples. A key geomorphic relationship is for larger features to respond largely to longer timescale processes [41]. However, at any particular scale, it is typical for smaller-scale morphology to provide a stabilising effect that partly or completely offsets the influence of sub-scale variations of environmental forcing, sediments or coastal structure.

The balance of erosion and accretion is an obvious form of sub-scale stabilisation, which results in rotation on partitioned beaches. Other responses, in order of increasing scale, may include steepening of the beach face, beach cusps, berms or bars[113]. These features have remarkable capacity to provide a stabilising influence, with each capable of modifying transport rates by a similar order of magnitude to overall transport rates. The presence of larger features is a general indication of high occurrence of conditions prompting sub-scale stabilisation. Consequently, they are more common in areas of bimodal forcing or structural features such as a change in beach alignment. For this reason, features such as beach cusps often recur at the same location. This mechanism is a major cause for the persistence of coastal features that otherwise seem out of balance with prevailing conditions.

Sub-scale stabilisation commonly takes two forms:

- Supply-limited conditions are those where the hydrodynamics suggest a transport capacity higher than sediment being supplied from the adjacent landforms. In this situation the landform adjusts rapidly to reduce the transport rate but is constrained by the landform sediment volume [114]. Examples include smoothing of the seabed, or formation of beach cusps. Deltas and barrier systems provide examples of large-scale supply-limited conditions, where the rate of sediment flux is more strongly a function of landform state than environmental forcing; or
- Rate-limited conditions, where the morphodynamics are limited by a maximum speed of geomorphic adjustment under strong but brief forcing conditions. Hence, for the brief period of forcing, the coastal configuration develops local source and sink areas, producing a trend towards a quasi-equilibrium state. Rate-limited behaviour is classically associated with ephemeral features such as bars and spits [113] although it may also be associated with geologically constrained or relict landform features.

Occurrence of these types of geomorphic stabilisation is strongly related to process timescales (Figure 11). Transition from rate-limited, through quasi-equilibrium to supply-limited occurs as the process timescale extends or intensity increases. Quasi-equilibrium occurs when the landform responds directly to the process regime, and is often implied inherently in modelling. Dissociation between forcing processes and landform response occurs under either rate- or supply-limited conditions and therefore has implications for numerical modelling applications [70,71,92].

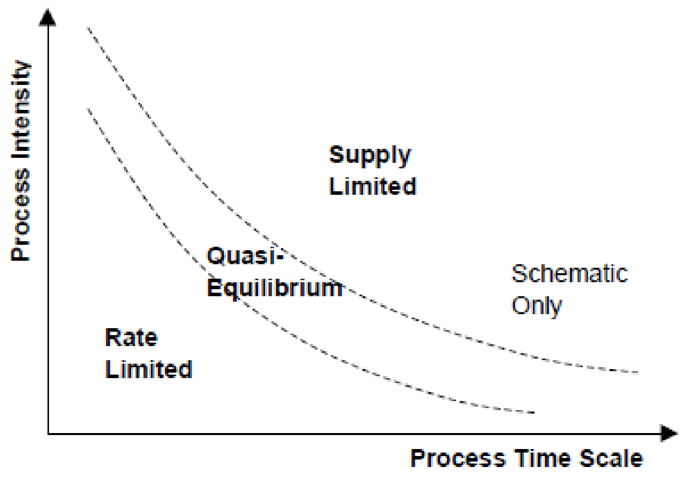


Figure 11: Process Intensity and Time Scale Influence on Geomorphic Response

4.3. Scale-relationships in Coastal Modelling

An extensive range of numerical and analytical models is available to describe coastal change for different timescales [115]. For each there may be a distinct suite of processes, applicable coastal configuration, different formulation and particular bias. However, the models can be broadly classed into three types, being short-term, medium-term and long-term modelling approaches [92,116]. These generally correspond to storm response, littoral drift and coastal evolution respectively (see Table 1). This challenges application of any approach to a different time scale, or the integration of more than one approach. For example, a small error introduced in a short-term modelling approach may dominate projection if it is applied over a long timescale [117]. Equally, the application of smooth response long-term modelling to short or medium time scales neglects the capacity for tipping point or state-jumping behaviour, and therefore under-represents coastal hazard.

Table 1: Assessment Characteristics Typically Associated with Model Timescale

Model Timescale	Short-term: Sub-annual	Moderate-term: Annual-decadal	Long-term: Supra-decadal
Main Process	Storm response	Littoral drift	Evolution
Main Direction	Cross-shore	Alongshore	Cross-shore
Scale in SW-WA	Up to 60m erosion [118]	20-100,000m^3/y [119,120]	~1 m/y change [111]
Volumetric Order	~100 m^3/m/y	~10 m^3/m/y	~1 m^3/m/y
Typical Key Assumptions	Rate of change determined by deviation from an assumed equilibrium profile. Alongshore flux is spatially nearly constant.	Erosion-recovery cycles are balanced around assumed equilibrium profiles. Impoundment occurs in few locations.	Equilibrium profiles move cross-shore in response to net volume change. No change to impoundment patterns.
Examples	Swart [121] Vellinga [122] SBEACH [123] XBEACH [124]	GENESIS [125,126] SBAS [127] Litpack	Bruun [81] RDA [93] STM [128]

The volume of sediment transport associated with each timescale reduces by an order of magnitude with each increasing step, suggesting that in the order of 90% of sand movement is associated with storm erosion and recovery. However, storm erosion-recovery cycles commonly produce oscillatory patterns of transport, potentially reducing net sediment movement by more than an order of magnitude over extended timeframes [c]. The influence of alongshore transport is similarly an order of magnitude greater than evolutionary rates. However, the potential for resultant change is determined by the balance of littoral drift in and out from an area, and is therefore indicated by transport rate spatial gradients. On 'open' straight coast, this gradient is very small and therefore reduces to a similar order of magnitude to the potential evolution rates. For a partitioned coast, the interplay between coastal rotation and bypassing may require use of shorter timescales to describe alongshore transport than typical on an open coast.

The compartmentalised nature of the Swan Coastal Plain provides locations where the alongshore transport gradient is high, such as the southern flank of Becher Point, north of Mandurah. This situation allows increased rates of change, and is reflected in the size of Holocene strandplains between Mandurah and Rockingham [111]. However, this pattern is not evident in contemporary coastal change, suggesting that the compartment has locally reached a point of sediment saturation or reduced supply.

The Busselton-Rockingham recession study [111] notes that the Swan Coastal Plain displays apparently low rates of onshore sand feed compared with other beaches [45,129]. When combined with the potential for locally steep alongshore transport gradients such as caused by 90^{o} change in shore alignment, there is suggestion that behaviour of a compartmentalised coast may differ significantly, particularly on a local scale, from the cross-shore dominated model prevalent in coastal modelling.

In their individual application, there is a characteristic switching of the main direction of coastal change between the three timescales, with short- and long-term change being cross-shore, while moderate-term change is mainly alongshore. This general behaviour is used conveniently in numerical modelling, through a zero-sum assumption over smaller timescales, to avoid the computational constraints offered by high-resolution modelling over long timescales. However, it often leads to interpretation problems and creates difficulty in public communication strategies when processes that are evident and actively managed (e.g. downdrift erosion) are not displayed by the model. Alternatives to provide improved modelling performance include nesting of multiple model scales that match key process scales, or sequential aggregation of model outputs, with disaggregation potentially required to communicate results effectively. Techniques of shifting scales through aggregation and disaggregation are termed upscaling and downscaling respectively (see Section 5).

Other key assumptions commonly used within coastal change modelling include equilibrium profile behaviour, small spatial gradients of alongshore sediment flux, limited capacity for impoundment and no change to (alongshore) impoundment patterns with net volume change. These complicate the different assumptions implicit in the three key approaches. Here impoundment refers to the storage of additional sediment within a landform, which may involve retention of alongshore transport (e.g. updrift of a headland), or vertical accumulation (e.g. within estuaries or on dunes).

[c] Common exceptions are introduced by relict or antecedent morphology, coastal structure limiting onshore-offshore movement (e.g. perched or terraced beaches) or engineered sections of coast.

Not all models used to represent the same suite of processes use the same set of assumptions, and it is typically through interpretation of morphology that a model practitioner will identify whether the model is appropriate. Alternatively, morphodynamic observations may be used post-modelling to verify short- or medium-term model performance, although often limited to describing overall change.

Few sets of observations can be used practically for verification of long-term modelling, particularly for representation of projected sea-level rise. Observations of medium-term change, particularly the 'step' change in mean sea-level from 1993 to 2012 due to a shift from El Niño to La Niña–dominated conditions can be used to suggest a qualitative vector for coastal change. However, the effect of timescale dilation suggests that long-term process-response is likely to be larger, along with the potential effect of changing patterns of sediment impoundment. The magnitude of dilation is a significant source of uncertainty, which is often quite arbitrary, such as a factor of two for closure depth [90], or zero dilation implicit in the zero-sum assumption often used to avoid cross-shore dynamics from medium-term coastal change modelling.

Scale relationship importance for sea-level rise impact modelling on a compartmentalised coast is demonstrated by the strong challenge to key assumptions at a boundary such as a headland, prompting the concept of 'lag erosion' (see Figure 12). Further challenge is brought about on a receding coast, as structures shift from being 'saturated' with sand, creating new areas of impoundment and causing spatially variable alongshore sediment transport. In parallel, effects of sea-level rise may be to reduce sand retention by coastal features such as reefs and perched beaches.

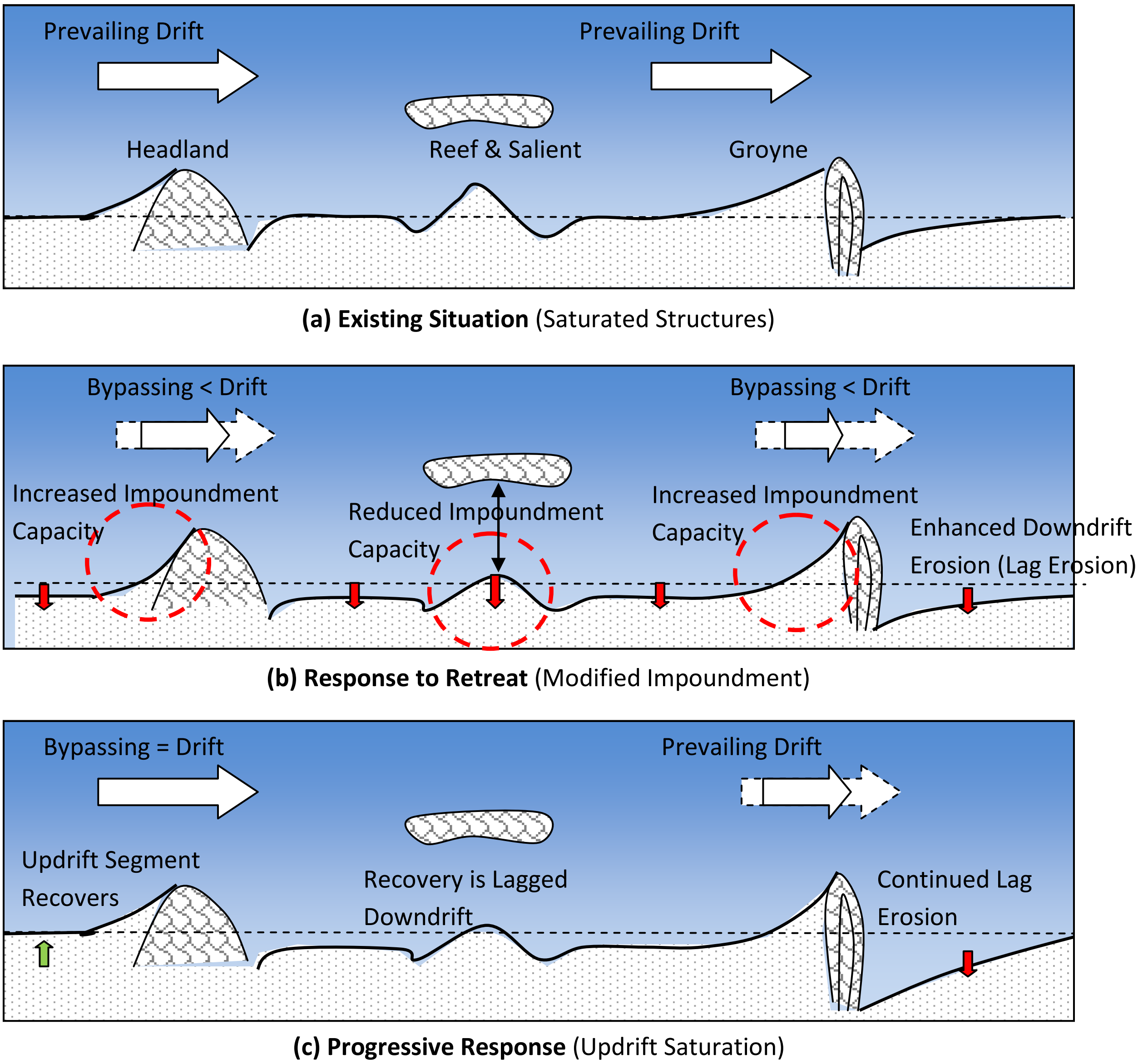


Figure 12: Influence of Compartments upon Coastal Change Sequence

4.4. Coastal Modelling Techniques

Diverse techniques for the prediction of coastal erosion, including responses to sea-level rise, are widely described in international literature, including empirical, statistical, analytic and numerical models. Three discrete forms of assessment are available:

- Proxy-based assessments (e.g. US coastal vulnerability assessments [130,131,132])
- Sediment budget-based assessments (e.g. SBAS, STM, GEOMBEST [133])
- Process-based assessments, which include numerical modelling (at small [123] or large [134] scales) and physical modelling.

Techniques within each of these forms are fundamentally distinguished by an array of classification schemes, which are generally determined by coast types (e.g. sandy, rocky, cliffed, embayed); driving conditions (wave or water level ranging); or geological origin [135]. The Bruun conceptual model for erosion due to sea-level rise is a simple sediment budget-based model for sandy coasts based on cross-shore balance [81], later extended through definition of closure depth [90] in an effort to cover a wider range of situations. The validity of this model has been widely debated, including presentation of loose supporting evidence [91], commentary from the original author [38] and extensive critique from others [84].

The simplification of assuming that coastal response to sea-level rise is entirely determined by cross-shore processes is prevalent within assessment methodologies, despite the importance of alongshore transport gradients being identified [136]. Another dramatic simplification is brought about through use of the Bruun conceptual model, which exclusively considers infilling of the nearshore zone to be balanced by erosion of the beach and dune. Alternative coastal response pathways have been identified in scientific literature, including cross-shore processes of dune impoundment, overwash or bar growth (see Figure 7) [82], together with estuarine sedimentation and trapping of sediment updrift of rock headlands. Adequately capturing the relative importance of these processes is important for the coastal sediment volume (i.e. available land); tracking of coastal change to allow decision-making triggers; and identification of on-ground mitigation or adaptation pathways.

Three levels of complexity for coastal modelling can be identified in geomorphic literature:

1. Landform elements (e.g. dune height, beach slope, presence of cuspate features) and active processes are assumed to continue unchanged;
2. Landform elements are assumed to remain constant, but a change in the balance of active processes is expected; and
3. Relationships between landform elements are considered to be dynamic, resulting from changes in active processes.

For practical reasons, the majority of coastal change assessments use the simplest approach, with the alternative approaches only applied where it is apparent that simpler methods are invalid, including occurrence of geomorphic tipping points [d]. Where evidence regarding the system complexity is not collected and applied to the modelling process, assessment results may be systematically biased according to the relative validity of the approach.

[d] Geomorphic tipping points occur when there is a dramatic change in the incremental coastal response to a change in environmental forcing. Typically they occur when an environmental parameter reaches a threshold at which there is a fundamental change in active geomorphic processes. The most apparent geomorphic tipping points related to sea-level rise correspond to vertical thresholds on the shore profile such that the change in active or dominant processes acts to

5. Scale Transfer within Geomorphic Frameworks

The key benefit of using a hierarchical geomorphic framework is to provide significantly improved capacity for comparing sparse information evaluated over different scales. This is particularly important for evaluation of coastal information, which commonly only describes a portion of the coast. The techniques of shifting information between scales are termed upscaling, moving towards larger spatial units, and downscaling, moving towards finer spatial units (see Figure 13).

In the rare situations where there is sufficient information to wholly describe a larger spatial unit, upscaling may involve averaging or extracting the maximum value. However, in most cases, it requires a meaningful synthesis of the information, which may be a weighted sum, equation fitting or a spatial krig (geospatial interpolation). The process of upscaling therefore involves some loss of fine-scale information. Upscaling is commonly undertaken for the purposes of reporting, although this may obscure the technical merit of the assessment or devalue performance measures.

Downscaling is required where coarse information lacks internal variation. Consequently, some information must be added to provide a fair representation at a finer resolution. This may be as straightforward as defining internal trends based upon the overall trend of the coarse information, or more complex, such as recreating characteristics typically observed at a smaller scale, including the influence of rock.

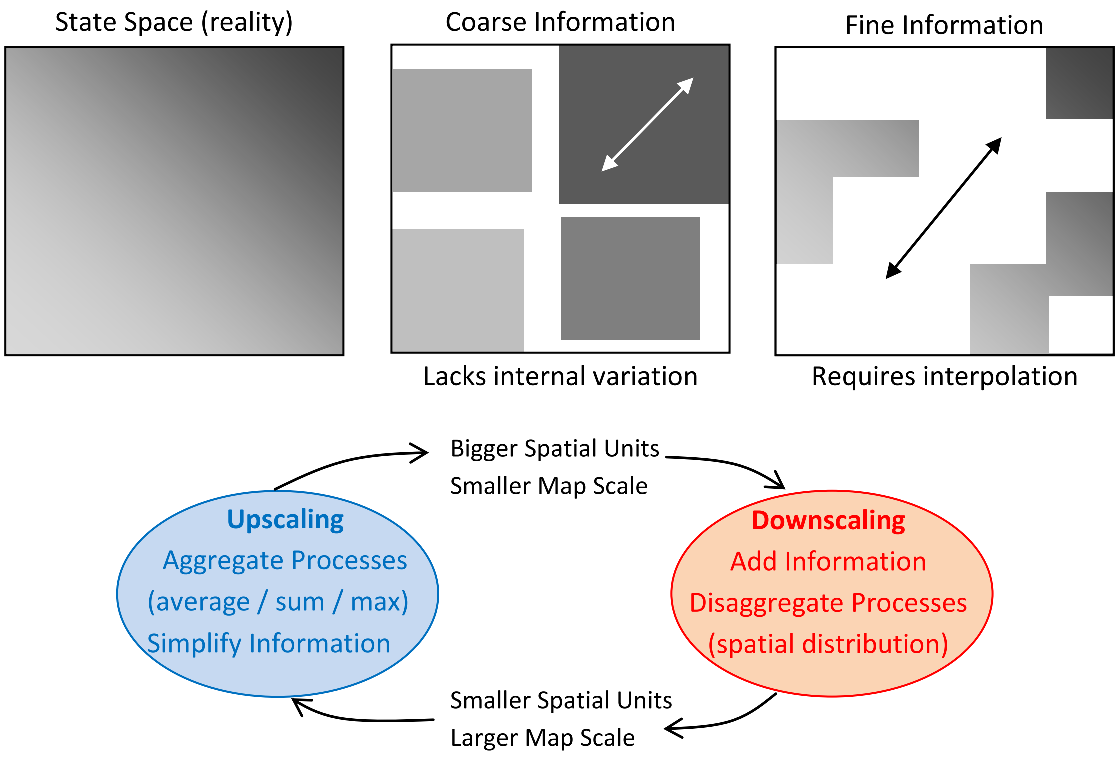


Figure 13: Notional Concepts of Upscaling and Downscaling

reinforce the effect of sea-level rise. One such threshold is the dune crest, where a sea-level rise may potential shift active processes from Aeolian to marine, with washover causing dune crest deflation and consequently amplifying the morphologic change.

5.1. Upscaling

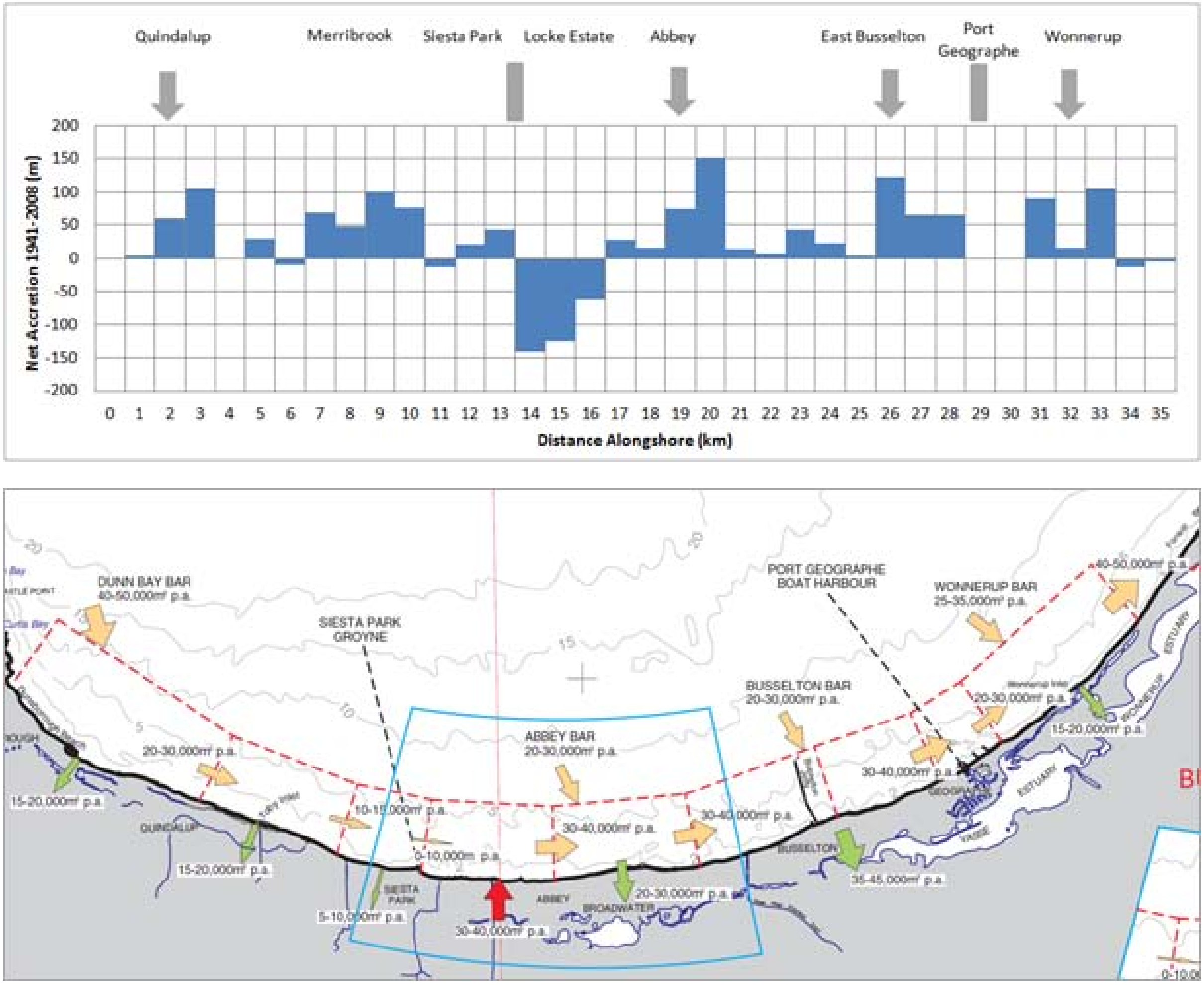
Upscaling involves the translation of information from a fine scale towards interpretation at a larger scale, which involves a process of aggregation. It is a necessary process for holistic management when the effect of behaviour at a small scale may affect the wider distribution of change. Reasons for undertaking upscaling occur for both analysis of observations and projection of potential change, along with convenience for reporting. Interpretation of behaviour over different scales often uses conservation of volume, or a zero-sum assumption to distinguish between key processes.

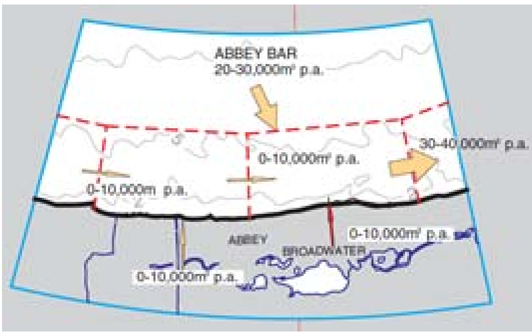
Upscaling is primarily used to relate or differentiate processes or characteristics that are active over different scales. For example, historical shoreline change from 1941 to 2008 within southern Geographe Bay demonstrates significant local variation (see Figure 14), which can be largely explained by onshore sand feeds and large groynes at Siesta Park and Port Geographe. Aggregation over the whole section of coast indicates that there is a net rate of accretion, while aggregation over intermediate scales demonstrates the effective degree of bypassing occurring at each restriction to alongshore transport, and enables a sediment budget to be inferred. In this case, the distribution of shoreline change within each of these sub-cells also suggests that alongshore sediment transport provides a key mechanism for change in southern Geographe Bay over supra-decadal timescales.

Projection of coastal change that is modelled at a fine scale requires aggregation when there are locally significant perturbations in response and potential for that local change to interact with adjacent areas (i.e. a distributed response). This requirement is strong on barrier coast [137,138] and deltaic systems [139], where change that occurs along 5–10% of the coast length may contribute an equivalent volumetric change distributed across the remaining 90–95%.

The aggregative approach may also be appropriate for the treatment of geometric or structural characteristics when they are being interpreted for modelling of larger scale processes. Finer scale elements that may be considered include elevation, grade, underlying geological formation, landforms or landform systems. Several different techniques for aggregation to generate representative cross-sections have been applied to the Busselton to Rockingham coast [111]. A key aspect to consider is relative sensitivity, with existing published literature and geomorphic models providing a substantial basis to support the selection of processes, scales and morphologies for aggregation.

An indication of requirements for upscaling (aggregation) across a sediment cell is demonstrated by the relative connectivity of observed coastal changes. This has been shown for 15km of beach along Perth northern metropolitan coast (see Figure 15) [140] and for a much larger 165km long cell on the California coast [73]. These studies highlight the need to identify how spatial variation may occur across a cell, as there is considerable variability of sediment exchange within cells and insufficient coverage or inadequate weighting may produce aliasing or significant bias. For example, on the Perth coast, the seasonal variation in beach width (Figure 15) suggests that South Port, Swanbourne and Floreat beaches are more exposed to winter storms than other beaches. The major characteristic that is required for upscaling is an understanding of the geometric coastal response to change, such that incomplete coverage by higher resolution information can be more accurately interpreted spatially.





Historic observations of shoreline change east of Siesta Park is unlikely to represent future transport. Coastal reorientation is believed to have reduced transport to near zero and may induce mild erosion in the Broadwater area (0-10,000m^{3}p.a.)

Figure 14: Southern Geographe Bay Shoreline Change and Inferred Sediment Budget Extract from Damara WA (2011) [141]

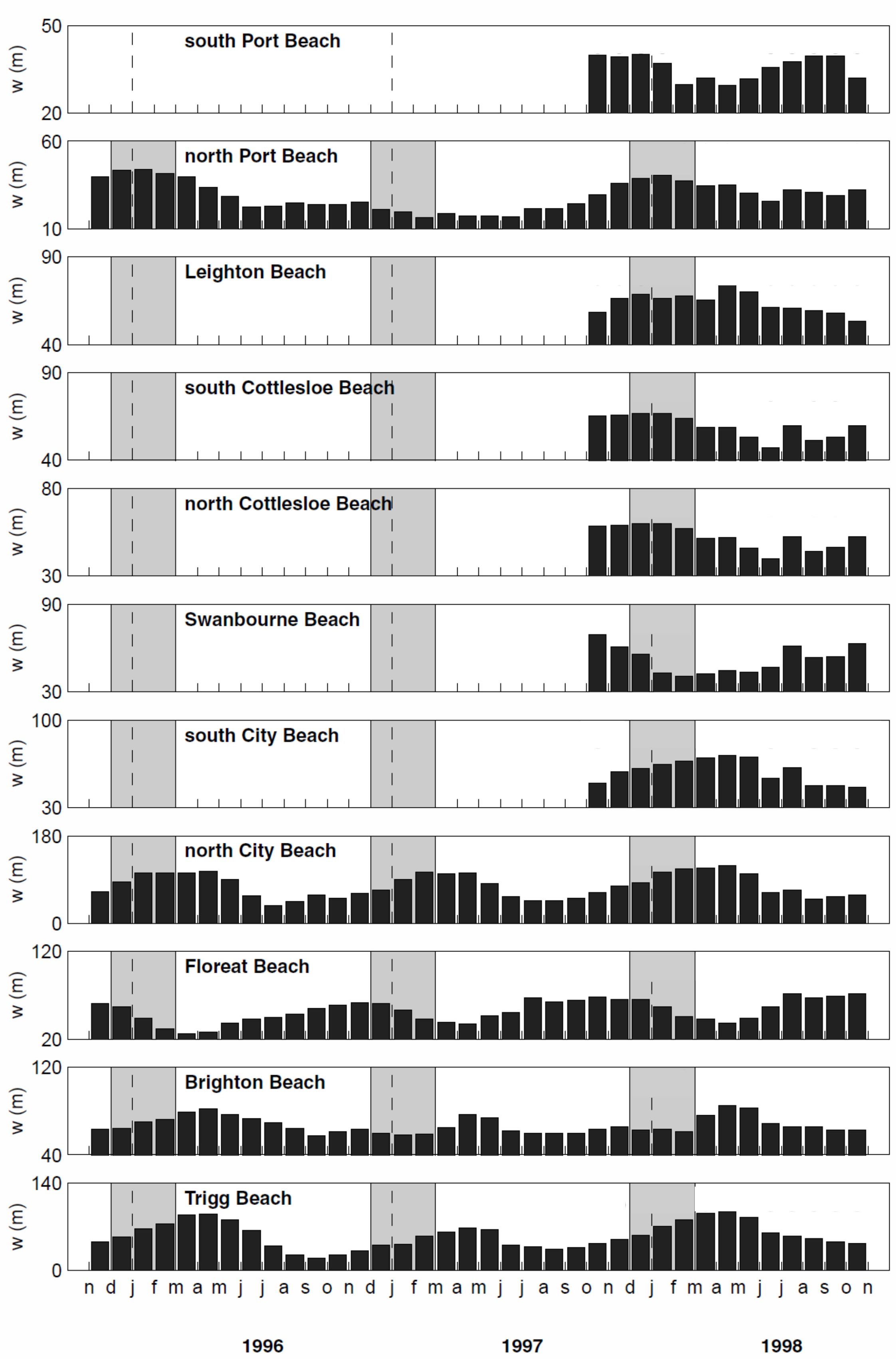


Figure 15: Perth Northern Metropolitan Area Beach Width Observations Extract from Masselink & Pattiaratchi (2001) [140]

The key technique for aggregation involves consideration of the behavioural similarity between fine-scale elements, with clustering of elements used to identify uniform models for change, which are then progressively added. The approaches of spatial 'averaging', selection of a 'representative profile' or characterisation via 'low points' are simple forms of aggregation, but in certain situations, they may work poorly at larger scales. Potential sources of error include neglecting the retentive capacity of rock headlands, the capacity for beach to dune sediment transfer, or the influence of breaching through dune low points.

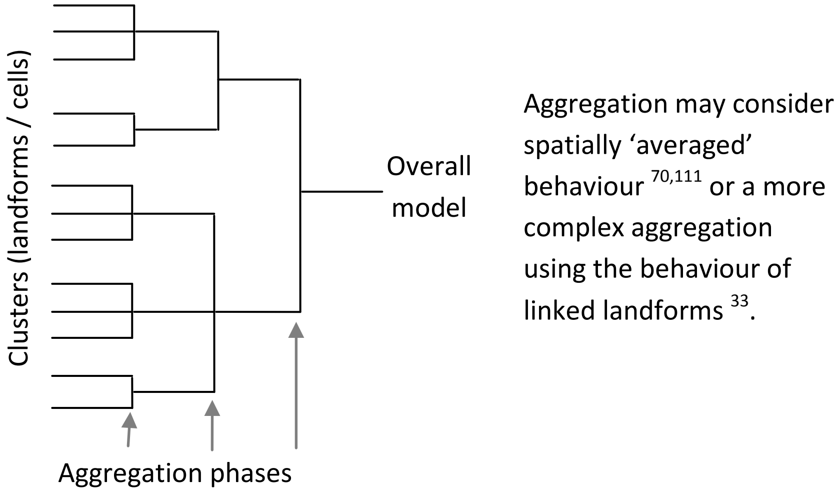


Figure 16: Concepts of Clustering and Aggregation

Approaches towards aggregation of characteristics within a sediment cell may involve integration of high-resolution data (e.g. shoreline mapping at <100m intervals on aerial photographs), regularly spaced monitoring profiles, or selection of representative transects. An example of applying minimal coverage is suggested for short beach segments within the Owen Anchorage, where transects are affected by response to coastal structures (see Figure 17).

High-resolution LiDAR/LADS bathymetry is available for some areas, including at a regional scale for the Peron–Naturaliste coast. This data typically requires upscaling through gridding, TINs, kriging or spatial aggregation when incorporated into coastal change studies. However, the act of upscaling should be undertaken deliberately, as LADS data over a range of scales may also be used to help identify rock features, indicate sediment transport pathways, and suggest the areas in which different processes are active.

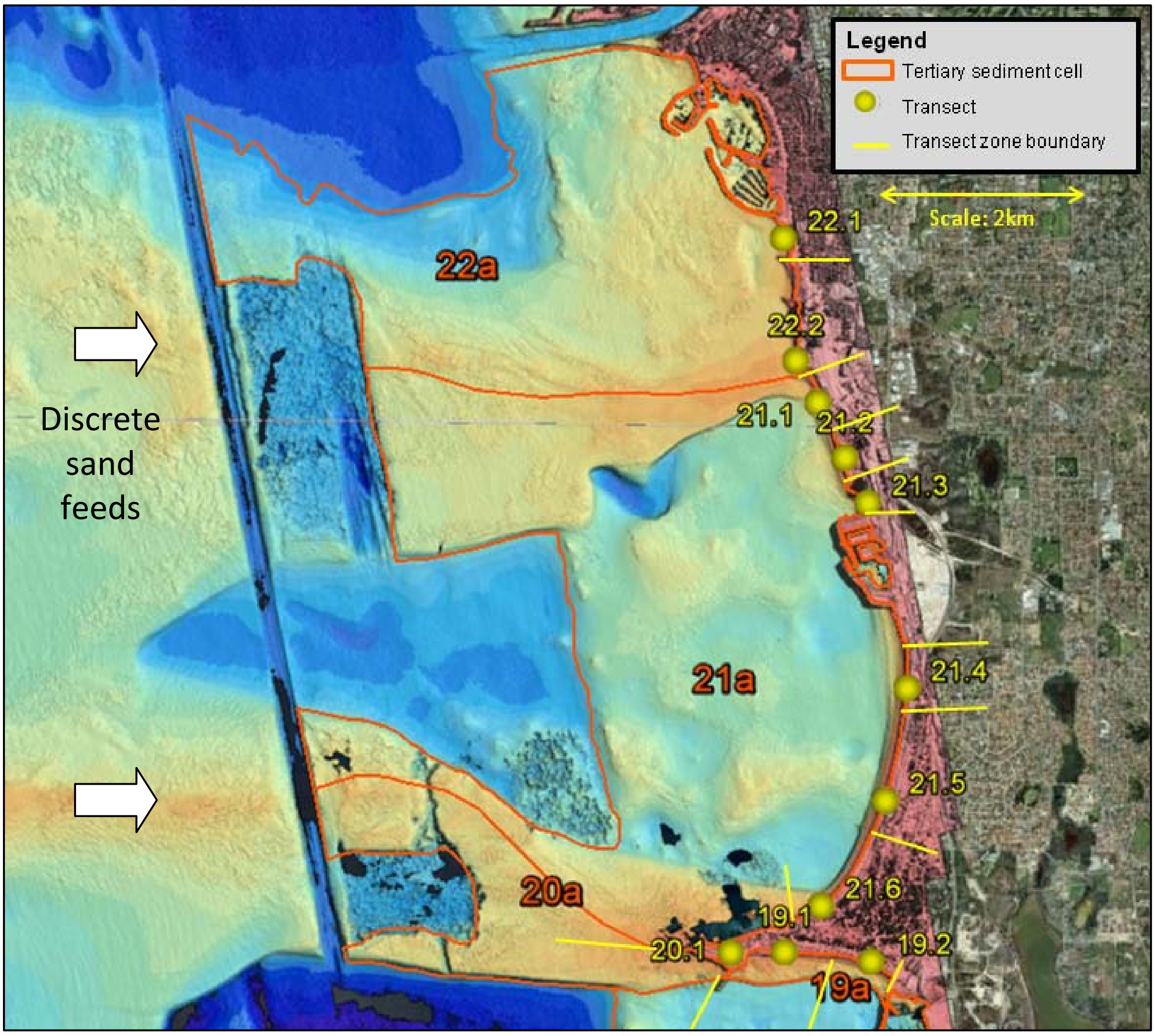


Figure 17: Owen Anchorage 'Representative' Transects

5.2. Downscaling

Downscaling involves the translation of information from a coarse scale towards interpretation at a finer scale. In order to provide meaning, downscaling requires the input of additional information to indicate how a process may be distributed within a larger spatial unit. The most relevant application to the question of response to sea-level rise is whether material eroded from shore–shelf transfer is unevenly distributed. This explicitly defines relative coastal sensitivity to sea-level rise (between sites) and therefore is critical for site selection, regardless of uncertainty in response scale.

For the Peron–Naturaliste coast, available landform mapping suggests that coastal response is unevenly distributed, with large-scale headlands playing a significant role (see Figure 24). This is illustrated schematically for a smaller coastal feature, showing updrift retention and downdrift erosion (see Figure 18). If headland response is not included in a recession study due to regional scale or uncertainty of response [110,111]; or a generic setback policy [26,27,80], then there is no differentiation regarding updrift and downdrift behaviour, neglecting a clearly apparent difference in relative exposure to erosion.

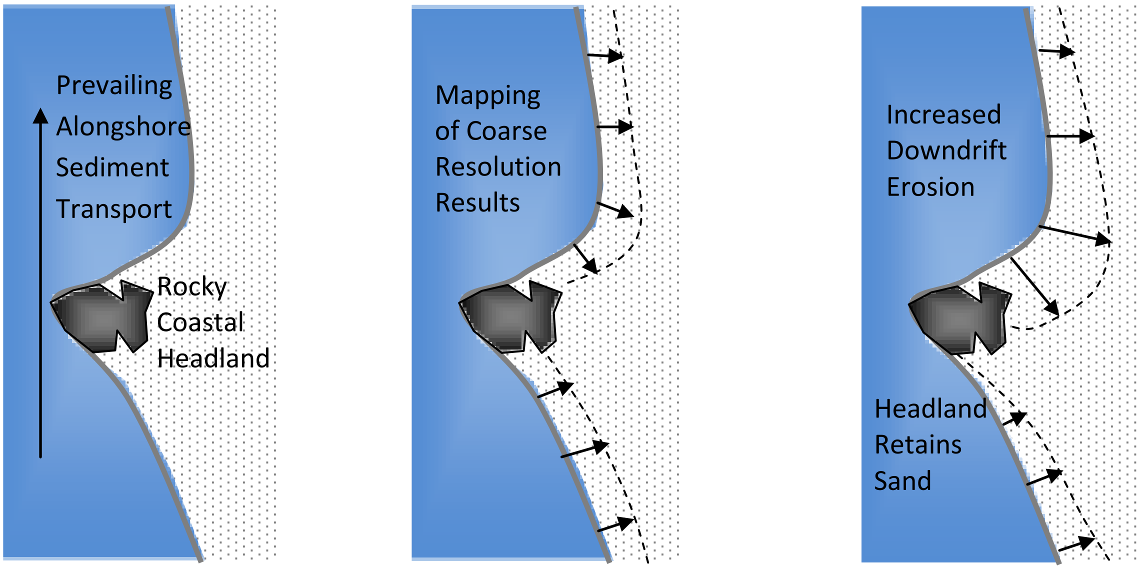


Figure 18: Downscaling at a Local Scale due to a Rock Headland

Downscaling for a compartmentalised coastal system is likely to require consideration of geometric characteristics. This may be as straightforward as assuming that coastal erosion is parallel to the existing coastal configuration. However, more complex approaches may be to consider zeta-form bay shapes [142] where appropriate, or consider the relationship between beach orientation and alongshore transport to suggest rotations of sub-cells that may result from a changing sediment budget [143].

A second form of downscaling is determined by restriction of alongshore transport capacity through sheltering or barriers to transport. These structures have been used as a primary element for definition of sediment cells (Appendix C), and typically represent a 'leaky' boundary rather than a total barrier or closed boundary. Evaluation of 'total' sediment within each cell based on demand and supply is then used to forecast coastal structure, in turn projecting effective transfer (see Figure 19).

The influence of geological controls is typically state dependent, affected by both the amount of recession and the scale of sea-level change. As discussed in Section 4, this may include the exposure of additional rock structures retaining sediment, or reduced influence of structures allowing sediment sources to be newly mobilised. This may have implications for the modelling framework, including the time and space scales to capture such effects.

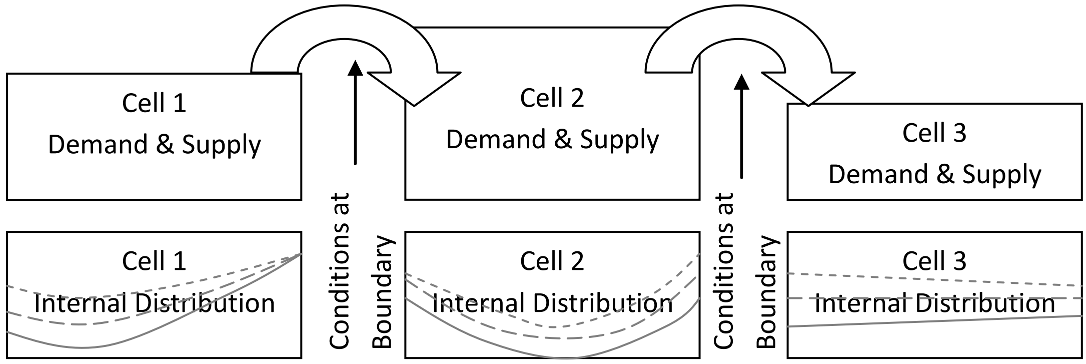


Figure 19: Conceptual Approach for Linking Cells

A complementary approach, scaled up from the design of coastal protection systems with multiple elements, is to consider impoundment associated with each coastal feature (boundary). Relationships between the volumes of impoundment and the degree of coastal recession may be used to estimate the quantity of 'free sediment' that is otherwise available for distribution along the larger network of cells.

5.3. Combined Upscaling and Downscaling

The greatest strength of the hierarchical geomorphic framework when undertaking sea-level rise impact assessment is provided by the combination of upscaling and downscaling (see Figure 20). In particular, the combination facilitates the use of sparse coastal data to provide a sound projection of coastal change that may be useable at a range of scales down to the infrastructure scale, i.e. tens of metres. The need for upscaling to provide integration of processes was demonstrated for the southwest coast [111], while corresponding constraints to use indicated the need for downscaling [144].

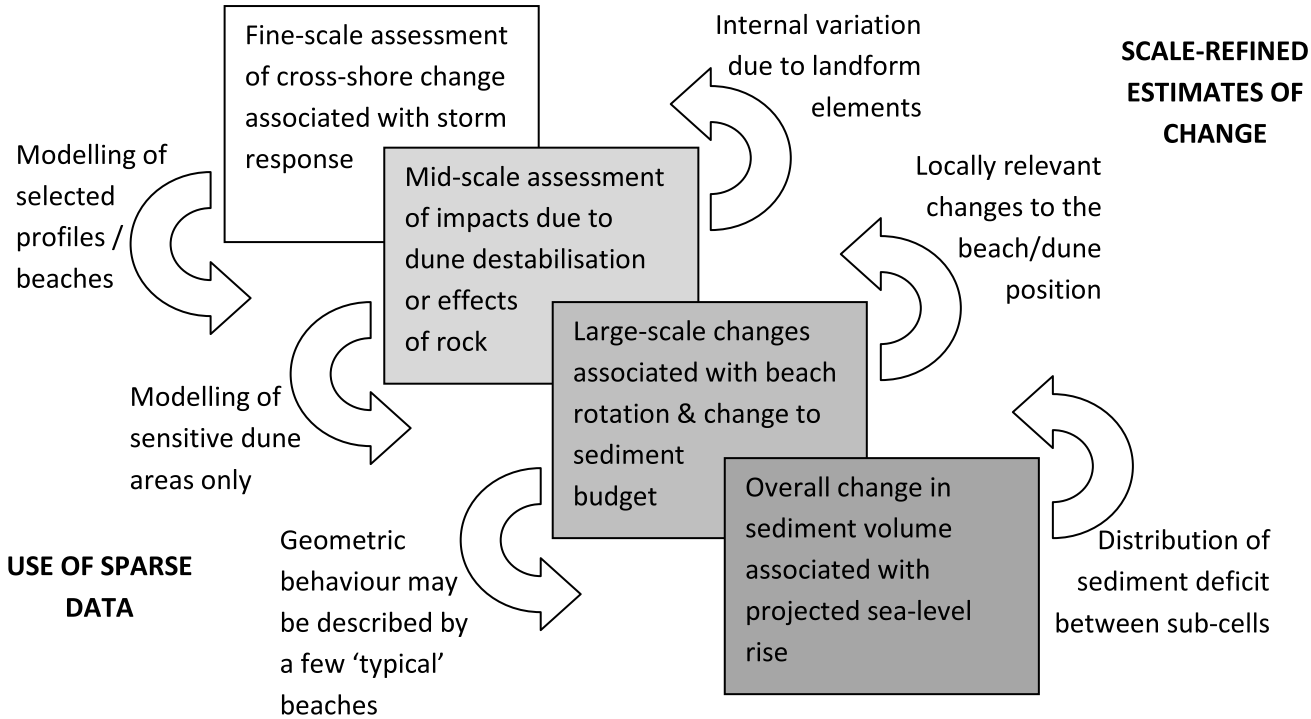


Figure 20: Schematic Integration of Upscaling and Downscaling

6. Examples from Western Australia

The Vlamingh and Pilbara Regions were selected to provide demonstration of the use of geomorphic frameworks to coastal change assessment in response to sea-level rise. These two Regions both are relatively data rich and display compartmentalised behaviour that has previously been assessed over several spatial scales. Hence, they illustrate the potential benefits of hierarchical evaluation and indicate the discrepancies that may occur between analyses at different scales. Although both Regions have compartmentalised behaviour, they are morphologically distinct, with the differences between their geomorphic characteristics highlighting the scope over which geomorphic frameworks may provide a practical means of improving sea-level rise impact assessment.

6.1. Coastal Morphology Context

The Western Australian coast has a very broad range of morphology, from the rocky cliffs of the Zuytdorp Region through to the silty sands and arid floodplains of the Pilbara Region [65]. Coastal diversity occurs through differences of exposure to meteorologic and oceanographic forcing [44]; the extent and structure of geological formations [75,76,77,78,79]; the role of riverine sediment supply [145]; and the length of time since relative sea-level caused a highstand over the late Holocene [48].

Classification of the Western Australian coast for the purposes of natural resource management (1000+ km scale) and regional planning (100–1000km scale) has identified that the significant variation in coastal landform types at these scales corresponds strongly with the regional geology [5]. On this basis, a set of 13 regions were identified, each typified by a different balance of rock and sedimentary features (Figure 1). The influence of rock structures is prevalent along much of the Western Australian coast due to limited sediment supply and the effect of a mean sea-level highstand approximately 1–2m above the present-day levels during the late Holocene [48,146,147]. For many parts of the coast, this provides a 'pre-stressed' condition, with sedimentary coastal features being limited in scale. The relative presence of cross-shore or horizontal rock features determines the degree of compartmentalised, perched or reef-influenced coast. Behaviour has been illustrated by sedimentological [67,148], shoreline mapping studies [119] and sediment management at coastal structures [120].

Demonstration of the role of geomorphic frameworks has been undertaken for the Swan Coastal Plain (Vlamingh Region) and the Pilbara Region. These areas have been selected mainly due to the availability of suitable high-resolution bathymetry, along with modelling and observations of coastal change. Significantly, these two areas also represent dramatically different morphologies. However a common characteristic, also prevalent for much of the Australian coast, including Western Australia, is the significant presence of coastal rock formations. Although headlands, reefs and platforms are commonly incorporated in models, their changing influence on a dynamic coast is often not evaluated. These formations play important roles in contemporary coastal dynamics and are expected to influence coastal response to projected sea-level rise.

6.2. Perched Beach Systems

Much of the Quaternary calcarenite limestone present around the coast of Australia, particularly along the coasts of South Australia and Western Australia, as well as the older sandstone topography of northwest Australia and the Northern Territory, is overlain or abutted by unconsolidated sand and silts of Holocene age. The morphology of shorelines, sandy beaches and dune systems in these areas spanning over half the Australian coast, is directly affected by complex interaction of marine processes with the geology at all scales. These are further complicated by regional disparities in hydrology, with marked contrast between arid areas and those subject to extremely high discharges from streams. In many instances, sandy landforms exist as perched beaches or dunes with very complex interaction between marine and terrestrial processes.

Interactions between marine and terrestrial processes are acknowledged where sandy coast is adjacent to rock outcrops in conceptual and numerical models describing wave refraction and diffraction [149,150], in the formation of cuspate forelands [151,152] and in the shape of embayments [153]. Sediment-substrate interactions have been subject to less investigation where unconsolidated sediments overlie or are fronted to seaward by rocky landforms [154,155,156,157,158].

Understanding of the role of the geologic framework in the functioning of sediment cells is not well represented in the available literature, either as conceptual models or through recognition of the role of rocky topography in the application of numerical models. Scope for further investigation and the development of appropriate models is provided by the increased availability of frequently flown aerial photography and LiDAR imagery. The significance of the geologic framework on mixed sandy and rocky coast is shown locally during a phase of accretion at Trigg, near Perth (see Figure 21c). Broad scale identification of sand sources and transport patterns may be developed from LiDAR images of the inner continental shelf. Examples from southwest Australia and the Pilbara are discussed in Sections 6.4 and 6.5 respectively.

Figure 21: Varying Sand Supply Mechanisms to a Perched Beach
Figure Collated by Shari Gallop
Source: Nearmap

6.3. Swan Coastal Plain

The Swan Coastal Plain forms the majority of the Vlamingh Region, and contains the most populated part of Western Australia, including Perth, Fremantle, Rockingham, Mandurah, Bunbury and Busselton (Figure 22). Characteristics of the Vlamingh Region include a temperate, micro-tidal climate, with low contemporary fluvial sediment supply and a strong relationship between the geological framework and contemporary processes.

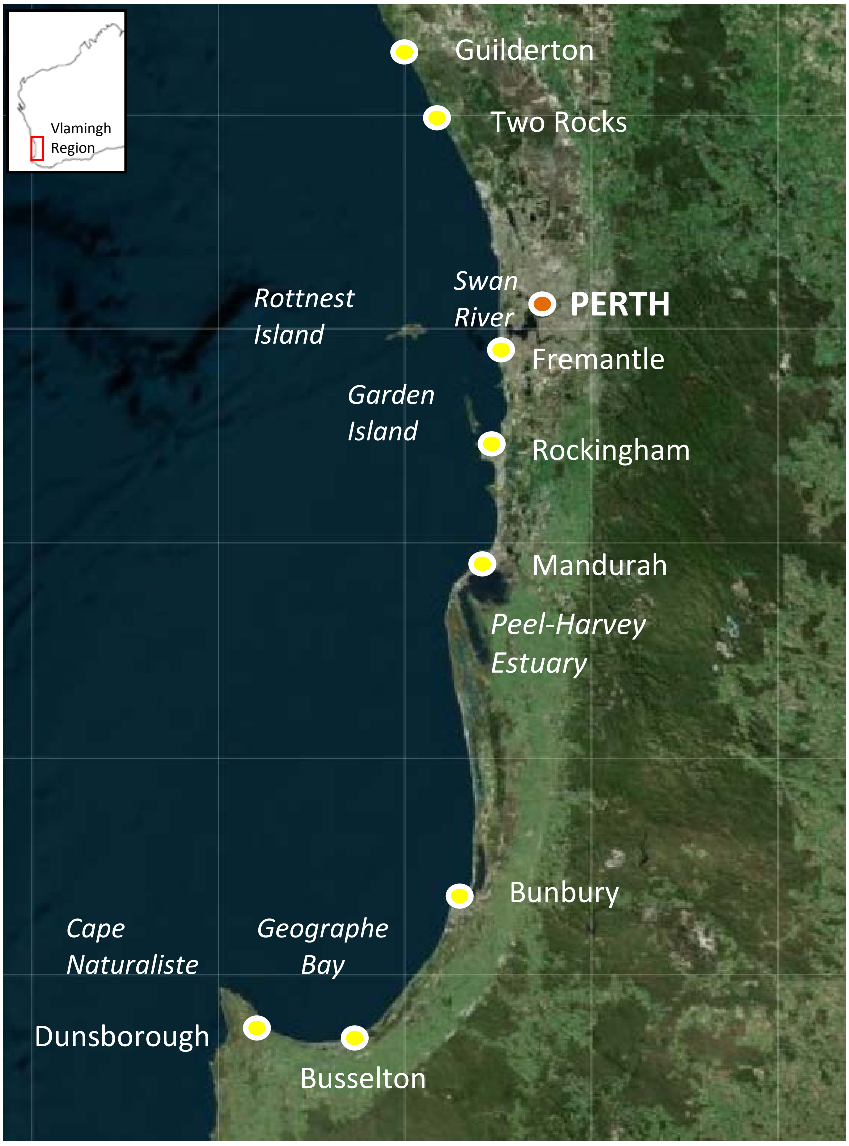


Figure 22: Map of the Swan Coastal Plain in the Vlamingh Region

6.3.1. Swan Coastal Plain Morphology

Between Cape Naturaliste and Fremantle is a broad coastal floodplain, mostly fronted by barrier dunes that insulate near-coast lagoons from contemporary dynamics. Limestone ridges developed as former shorelines and barrier systems occur as chains of reefs, islands and headlands, and are sub-parallel to the modern coast, with submarine rock platforms along extensive sections of the inner shelf [159]. The regional tidal range is micro-tidal, with an energetic offshore wave climate heavily modulated by reef-sheltering and diffraction due to Cape Naturaliste.

The broad and low gradient structure of both the floodplain and semi-arid hinterland east of the Darling Scarp provide limited riverine sediment input to the Swan Coastal Plain. The few estuary basins present are either relicts incompletely filled during the late Holocene, such as has occurred in the Swan–Canning Estuary [160]; predominantly filled with marine sediments such as in Peel Inlet [95,96,97]; or geomorphically modern features that have developed through barrier dune interruption of flood channels, which are present along much of the plain between Quindalup and Harvey.

Marine sediment is supplied to the Swan Coastal Plain from the area between Cape Leeuwin and Cape Naturaliste, arriving through onshore and alongshore sand feeds. Supply has been sufficient to cause historic accretion along the southern Geographe Bay coast, while contributing to net northwards alongshore transport artificially interrupted at Bunbury and Dawesville Channel. A local area of deposition occurs south of Becher Point, with a limited supply of marine sands travelling past the Garden Island ridge towards Cockurn Sound and Owen Anchorage. North of the Swan River entrance, Perth metropolitan beaches from Fremantle to Trigg form an almost self-contained sediment compartment with net northward transport, displaying seasonally oscillatory alongshore transport within internal cells[140]. Coastal behaviour along the Perth–Fremantle coast is strongly affected by anthropogenic management, including nearshore deposition of enormous quantities of dredged sediment, and active management through installation of coastal protection works [161,162].

6.3.2. Findings from Swan Coastal Plain Studies

Behaviour of the Swan Coastal Plain has been assessed through a diverse range of study scales and techniques. The majority of these studies have not been directly related to the question of response to sea-level rise, but have focused upon potential coastal land use. These have generally taken the form of either geomorphic studies describing the origins and natural instability of coastal landforms or engineering studies at a smaller scale that outline required management at coastal facilities including harbours, jetties, seawalls and dredged navigation channels [163].

Geomorphic studies have defined sub-regional patterns of similarity for coastal sediments, coined natural sectors [66], but have also identified focal zones of late Holocene deposition [164], relict deposits [96,165] or basins [166], as well as complex evolutionary sequences controlled by rock features [167]. Sand production within this region occurs from both erosion of rock features and bioproduction, with a sediment pathway from Rottnest Island towards Perth's northern beaches [168]. While sediment composition across the inner shelf can largely be described by a transition between the two sources around Mandurah, suggesting continuity, there are significant local discontinuities in the availability of sediments due to the influence of smaller-scale rock features. For much of the coast between Bunbury and Fremantle, sediment often occurs as only a thin veneer above limestone pavement.

Trapping and focusing of sediment provides discrete sand feeds, with large gaps in the Garden Island ridge forming the distinctive shoals in Cockburn Sound and Owen Anchorage over the Holocene [159,166].

Previous analysis of coastal erosion and accretion in Western Australia has strongly tracked the changing nature of coastal facilities and land use. Before dredging of Fremantle Harbour, almost all large coastal installations were deep-draft jetties to suit sailing ships, and therefore largely tolerant of coastal movements. Concerns regarding sedimentation of harbour basins were clearly recognised in the late nineteenth century, and decision-making regarding Fremantle Harbour was strongly influenced by evidence of limited sediment transport at the Swan River mouth, based upon adjacent landforms. The training walls (moles) built at the harbour entrance were built primarily for purposes of wave protection. Following the success of Fremantle Harbour and with vessel drafts reducing due to mechanisation, several extensive coastal facilities were constructed in more active coastal locations to manage shoreline variability or provide wave sheltering.

The long-term coastal response to the change imposed by more obtrusive coastal structures yields useful information about the processes active in the southwest. The major characteristic apparent is: net northwards drift of sediment is prevalent along the coast, with occasional short-term reversals reported at particularly sensitive operations such as Bunbury and Coogee power stations. The significance of information collected from the management of coastal facilities, including dredging and bypassing, is that it provides actual quantities of sediment transport, and therefore is fundamental to the verification of inferred or modelled estimates of change [111]. This was illustrated through synthesis of facility sediment management, shoreline change information and numerical modelling for the Bunbury to Mandurah coast to support design of the Dawesville Channel [119,169].

Recognition of potential coastal response to sea-level rise was formalised in policy through inclusion of an allowance when defining coastal development setbacks [80]. However, by providing a fixed methodology for assessment, this has partly stifled sub-regional assessment of the threat provided by sea-level rise. Furthermore, adoption of a constant allowance effectively ignores the relative susceptibility of different landforms, and ignores landform connectivity (e.g. estuary—coast interaction). This creates an unbalanced risk profile, with the allowance least conservative in areas of highest susceptibility (see Section 5.2). Several studies to investigate how responses to sea-level rise may vary based upon locally significant characteristics have been conducted, respectively highlighting the role of nearshore rock features at Cottesloe [170]; the effect of high supply through discrete sand feeds along the southern Geographe Bay coast [171]; and secular variability of alongshore supply and trapping at Scarborough [172]. In parallel with these assessments, the WA Government has funded a series of studies related to landform assessment [75], definition of regional-scale compartments across the state [5], landform-based coastal vulnerability analyses [18,19,20,21,22] and definition of local-scale sediment cells within the Vlamingh Region [173], for coastal management (see Figure 23).

Direct assessment of coastal response to sea-level rise has been undertaken on several occasions. The sensitivity of the low-lying Busselton coast was identified during an early application of the IPCC 'Common Methodology' for Sea-level Rise Impact [174], with evaluation of Perth metropolitan coast sensitivity later selected as one of the national coastal vulnerability case studies [175]. An erosion assessment along the Swan Coastal Plain evaluated the relative presence or absence of coastal limestone using geophysical methods and borehole logs, with a modified form of the Bruun model used to derive response to sea-level rise for sedimentary features [112]. More recently, a regional assessment of coastal response to sea-level rise was undertaken using heuristic uncertainty-based evaluation of change [111]. Large differences between these studies and local setback assessments within the Vlamingh Region has shown the dramatic effect that assessment methodologies and their interpretation may create. Significant differences may also occur between studies at the same scale, with interpretation of modified Bruun model suggesting that the Mandurah coast was the most stable due to alongshore sediment supply; while the uncertainty-based assessment, which included variation of alongshore supply, suggested that the Mandurah coast was the most susceptible to sea-level rise due to the potential trapping of available sediment supply.

The uncertainty-based assessment highlighted the significant unknowns associated with coastal response to sea-level rise. However, consideration of remotely possible physical outcomes (e.g. uniform infilling across the 35km wide shelf), along with direct inclusion of these uncertainties into the assessment, gave results that are difficult to use [144]. The regional uncertainty-based analysis suggested setbacks up to 800m, which contrasted starkly with the 100m typical for local setback analyses [163], making it difficult to match-up the behaviour identified at different scales. An interpretation of the regional recession study was undertaken through selection of refined scenarios of shore–shelf sediment exchange, and downscaling of recession distances using spatial patterns based upon landforms [176]. It was identified that downscaling could not be effectively achieved to the adaptation scale because geological information was not available at the scale required. As a consequence, the influence of rock features upon alongshore transport was neglected (see Section 5.2).

The importance of alongshore sediment transport for coastal evolution was further highlighted within sea-level rise impact assessment for the Cockburn Sound and Owen Anchorage coast[25]. The relict basins and development of sedimentary features indicate the role of discrete onshore sand feeds, and consequent distribution through alongshore transport. Installation of coastal structures and disruption of these transport pathways provided valuable insights into the workings of a highly compartmentalised section of coast.

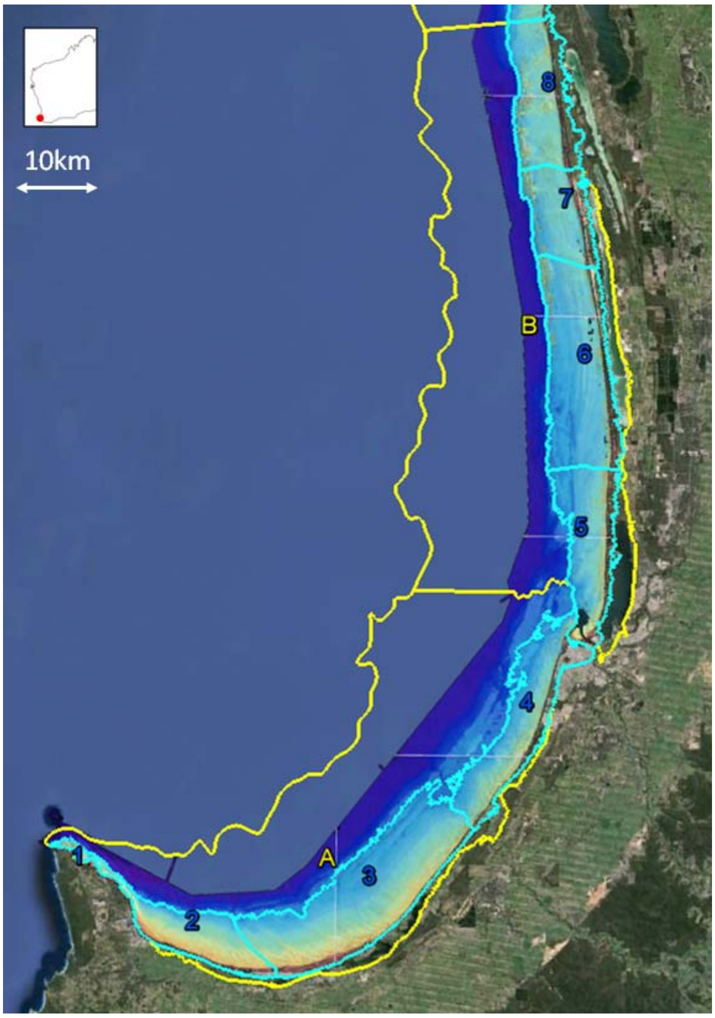


Figure 23: Sediment Cell Scale Example for Cape Naturaliste to Cape Bouvard
This is the southern part of the Vlamingh Region
From Stul *et al*. (2012) [173]. Background image from Google Earth.

The influence of coastal response pathways alternative to the Bruun conceptual model is apparent in southwest Western Australia when historic landform change or late Holocene landform distribution is compared with regional, sub-regional and local assessments of coastal change. In this case, it is acknowledged that the available regional assessment [111] was uncertainty-based and therefore encompassed a broad range of possible outcomes. However, as might reasonably have been expected, variation of recession lines along the coast did not display sensitivity to coastal types, which included low and high coastal barriers, reef- and platform-sheltered beaches and beaches perched atop low coastal cliffs.

The distribution of late-Holocene landforms suggests that the coast type, along with the retentive capacity of coastal headlands, provides significant influence upon the long-term pattern of coastal evolution (see Figure 24). Similar, evolutionary mechanisms have been interpreted from the stratigraphic record in the Perth metropolitan coast [177]. Local-scale coastal change assessments suggest that the role of overwash and consequent barrier growth is significant in the Busselton region, with substantially different patterns of coastal change projected if this process is neglected or under-represented. This behaviour is supported scientifically [37] and forms a fundamental part of the assessment of barrier coast morphology [138].

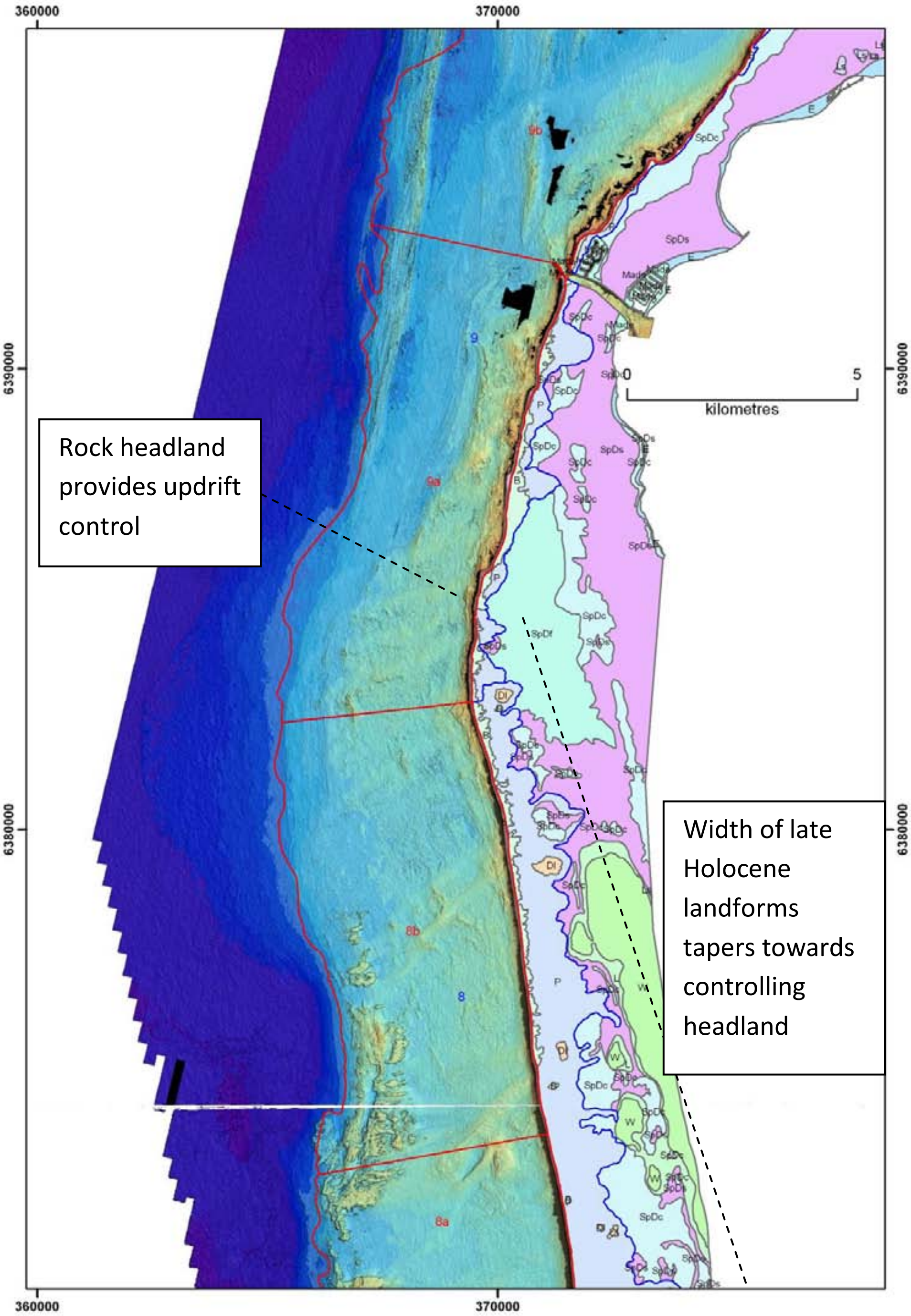


Figure 24: Illustration of Coastal Landform Spatial Distribution Extract from Gozzard (2011) [75]

Cockburn Sound and Owen Anchorage (see Figure 17) provide a local-scale illustration of the roles of different response pathways, with the more sheltered environment allowing the formation of terraced beaches and evolving through the alongshore transport of discrete sediment feeds from offshore. These conditions provide a slow response to long-term change, resulting in a largely relict structure. However, this slowed response also highlights the adjustment scales of the coastal units, with a response cascade (in terms of decreasing speed) of beaches, dunes, inter-tidal terraces and nearshore. While this relative speed of response is acknowledged in literature [70], the dynamics in Cockburn Sound emphasise that the long-term processes (such as represented by the Bruun conceptual model) are *additional* to the response of other coastal units. For example, barrier dune mobility due to sea-level rise may be a similar order of magnitude to shore–shelf exchange; however, unless deliberately identified, 'line models' and fixed morphology 2D transport models will not incorporate dune mobility. This perceived need prompted development of the X-BEACH model [124], although the model is not presently suitable for use at the time- and space-scales necessary to represent long-term coastal change in response to sea-level rise.

The significant value afforded by LIDAR and LADS bathymetry for the purpose of coastal landform assessment is suggested by the interpretations for Mandurah (see Figure 25), Binningup (see Figure 26) and Quindalup (see Figure 27), each of which roughly corresponds to cells or sub-cells from the wider Vlamingh Region (see Figure 23).

Mandurah bathymetry displays the major role played by the offshore calcarenite ridge, to focus sand supply through discrete feeds (see Figure 25). The arcuate structure of Comet Bay, with Mandurah at the south and Becher Point at its northern end, has a dramatic change in orientation, allows annual trapping and onshore movement of approximately 80,000m^3 of material, which is mechanically bypassed at Mandurah Channel ocean entrance to assist navigation [120].

The calcarenite ridge is dominant near Binningup (see Figure 26), where in parts it acts as almost a complete barrier to cross-shore sediment transport. The multiple ridges inshore of the main reef line appear to channel sediment alongshore, with occasional breakout zones. Sand waves occur within the nearshore gutter, with some connecting to adjacent features, including ties to coastal salient and welding to rock outcrops.

LADS bathymetry for the Quindalup coast, west of Busselton, illustrates the importance of evaluating active coastal processes at multiple scales (see Figure 27). At a large scale, the arcuate form of Geographe Bay, including Quindalup Beach, suggests dominance of swell-waves, which previously has been used as justification for modelled sediment transport rates. At a slightly smaller scale, undular bed features are present, apparently caused by underlying rock, which are likely to cause wave energy focus and dispersal. With further reduction in scale, nearshore sandbars (or exposed rock features further east) become the most apparent feature, with some convex coastal features associated with larger sandbars. At an even more detailed scale, it appears that the coastal alignment is developed through the combined influence of onshore sand feeds and alongshore controls, including artificial structures, overlying the more gradual variation produced by the wave climate.

Although this progression represents the effects of changing scale within only one sediment cell, a similar pathway should be considered when attempting to transfer between levels of the coastal hierarchy. Specifically to minimise errors which may be introduced by change of scale, it is important to determine what change in coastal response may be implied by any process simplification that is implicit to the change in scale.

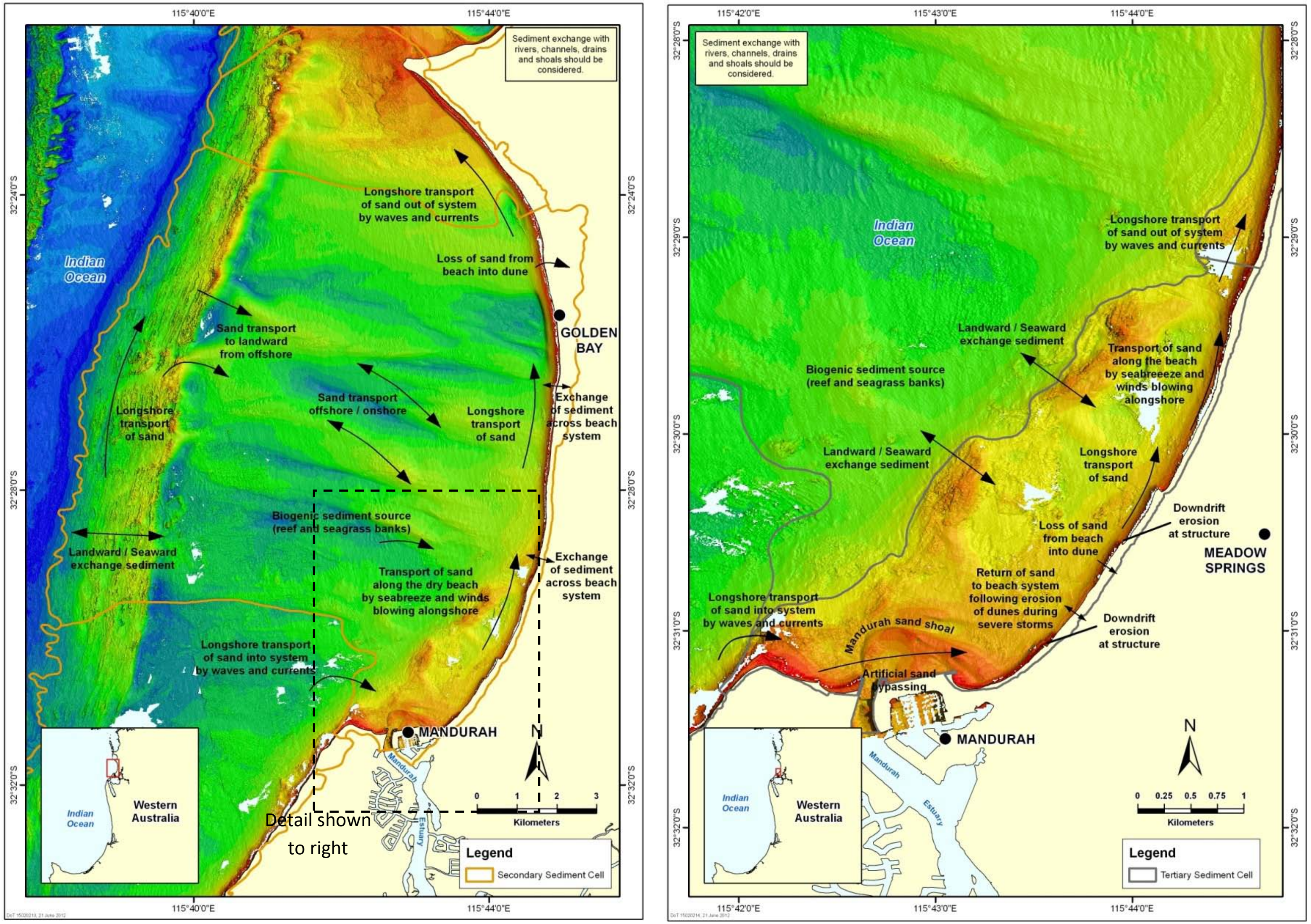


Figure 25: Interpretation of LADS Bathymetry near Mandurah
Extract from Stul *et al*. (2012)[173]

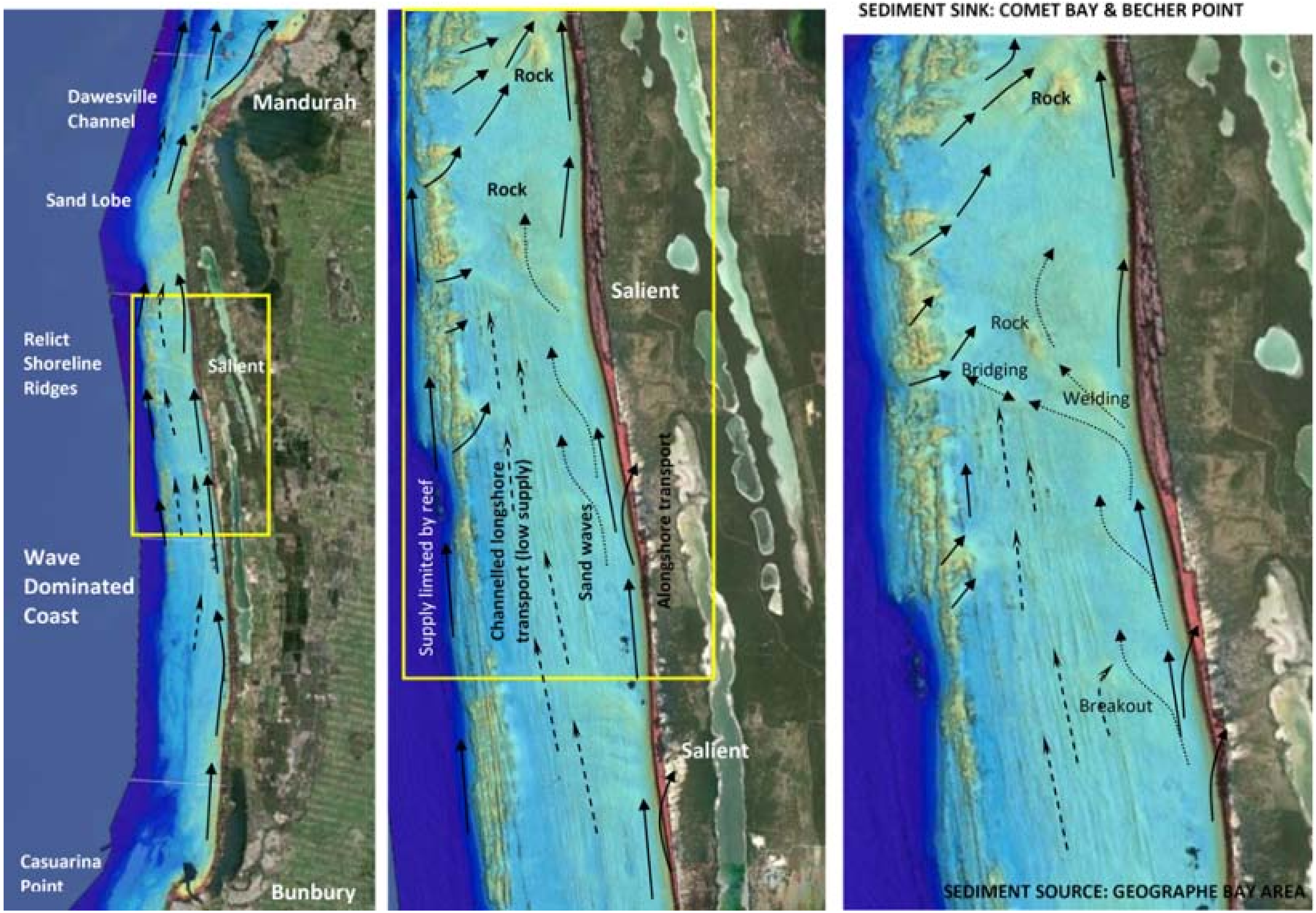
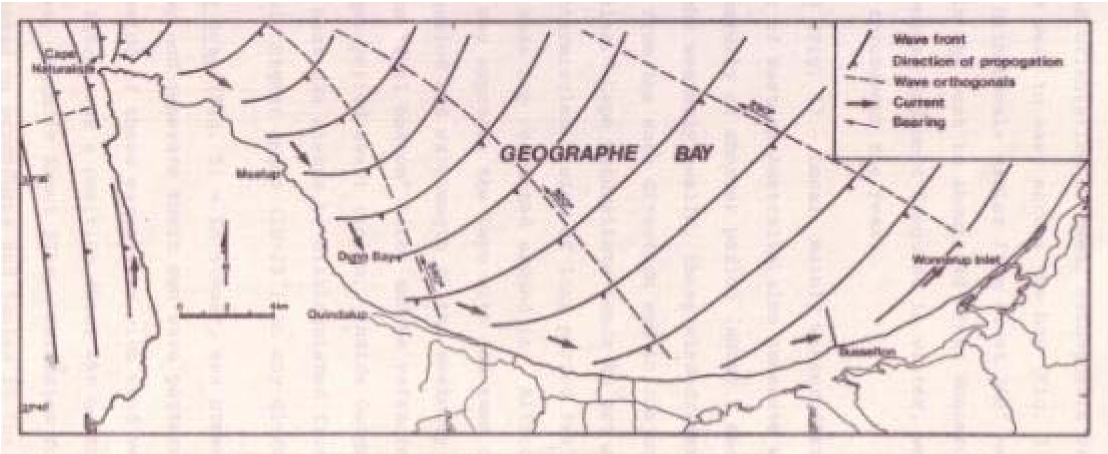


Figure 26: Interpretation of LADS Bathymetry near Binningup



Extract from Searle & Logan (1978) [178]

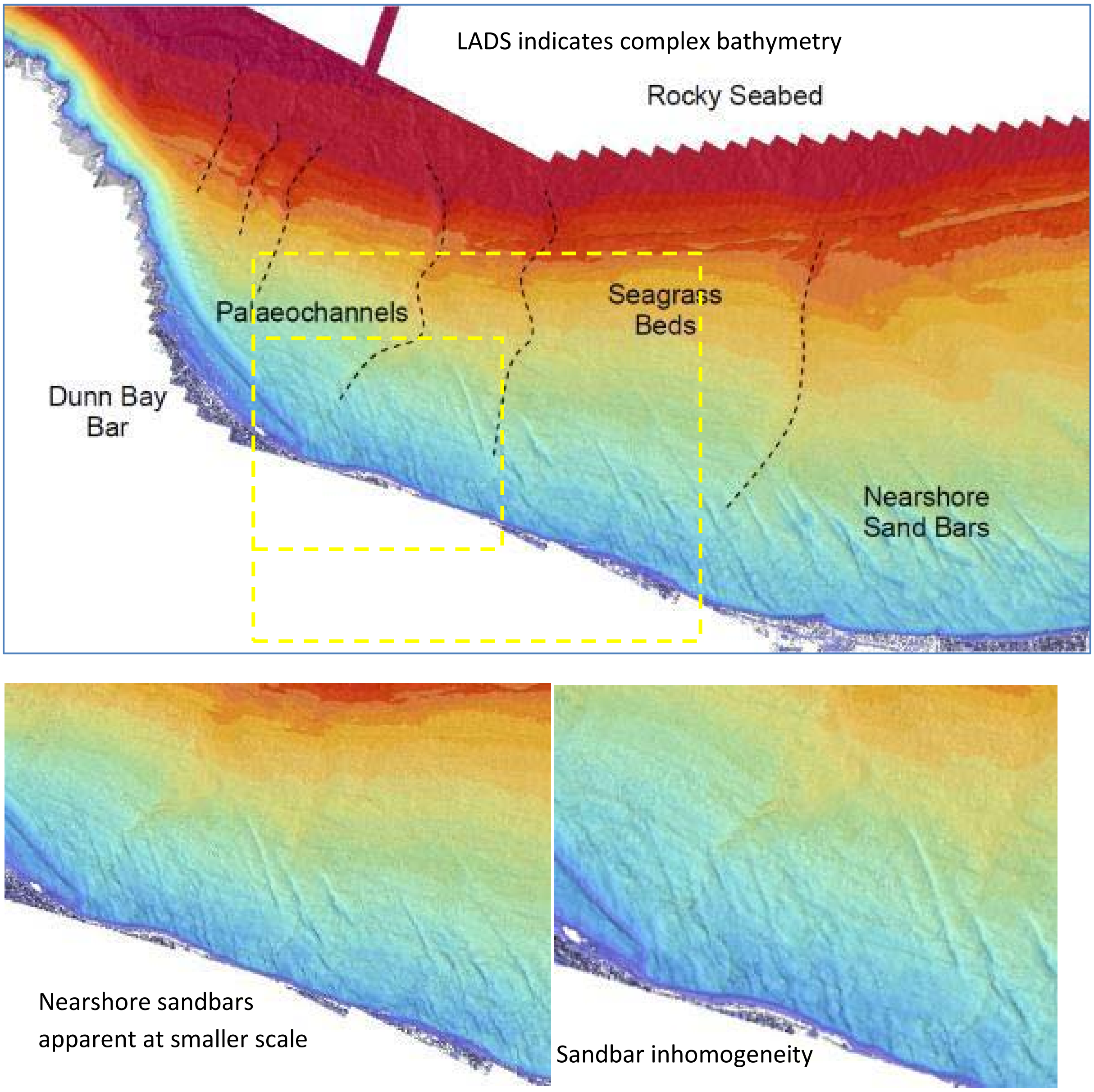


Figure 27: LADS Bathymetry near Quindalup

Coastal behaviour within the Vlamingh Region may be distinguished from the general model suggested for cross-shore balance (see Figure 6) due to the compartmentalised nature of the nearshore and onshore areas. This characteristic, particularly adjacent to offshore calcarenite ridges, funnels sand supply from offshore sand bodies through discrete paths; and causes highly variable alongshore transport rates (see Figure 28). A major consequence for projection of the coastal response to sea-level rise is that the role of alongshore transport requires careful integration with other mechanisms, such as shore—shelf sediment exchange. Sediment supply to the region is generally moderate [46], and for much of the coast is dominated by produced sediment. Onshore impoundment is typically low, possibly due to the remnant influence of the late Holocene highstand, with most coastal dunes well developed, such they are not subject to overwash.

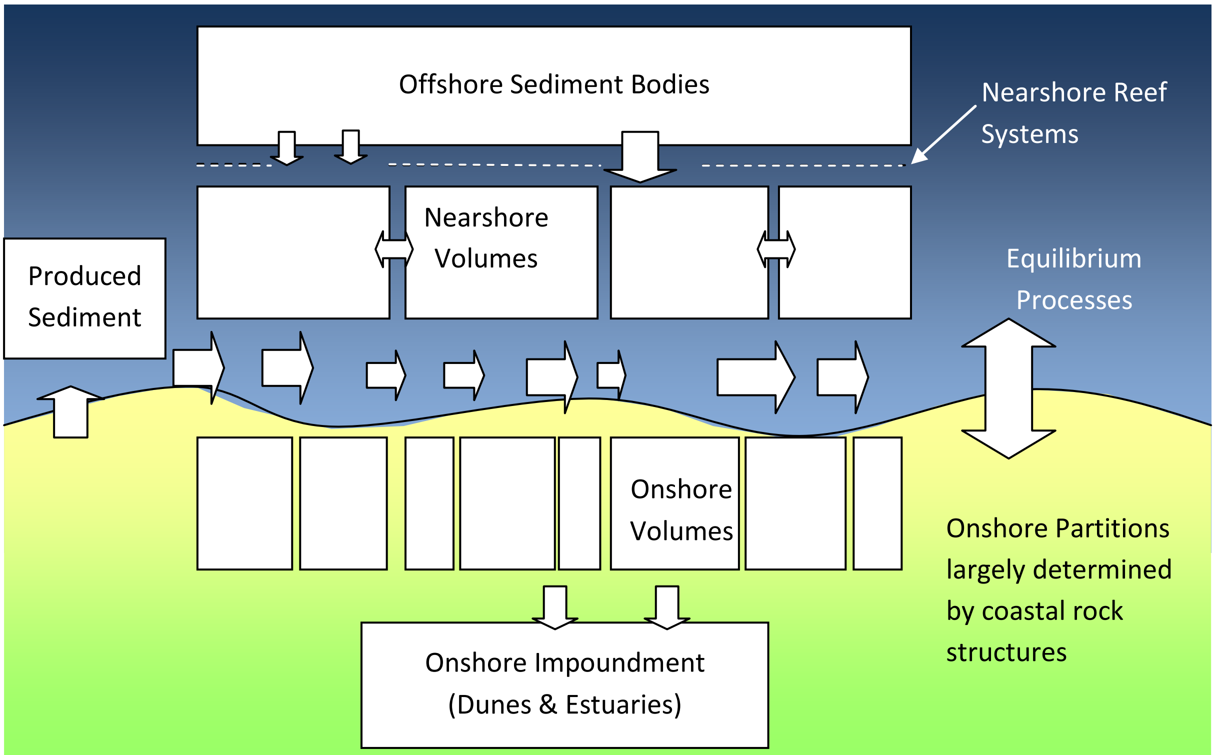


Figure 28: Schematic Behaviour of Naturaliste to Lancelin Coast
Produced sediment is from rock erosion and biogenic production, including seagrass and epiphytes.

Some aspects of the behaviour of a compartmented coast may be inferred from historical coastal management within Cockburn Sound and Owen Anchorage. Fluctuations of supply from onshore sand feeds and the effects of groyne installation impose changes to the alongshore transport rates and net sediment deficit that parallel the impacts of sea-level rise (see Figure 29). The effect of mild reductions to sediment availability is typically not evident while a beach segment is 'saturated', except possibly towards the end of a chain of beach segments. Reduced supply merely causes a corresponding reduction in the rate of material leaving the segment.

If supply reduces below the sediment demand[e] of the beach segment itself, then erosion will begin to occur. The positioning of the erosion is determined by the internal transport patterns within the segment. For a beach with low transport, supply fails to reach the end of the segment, causing erosion towards the downdrift end. Under high supply conditions, erosion is focused towards the updrift end.

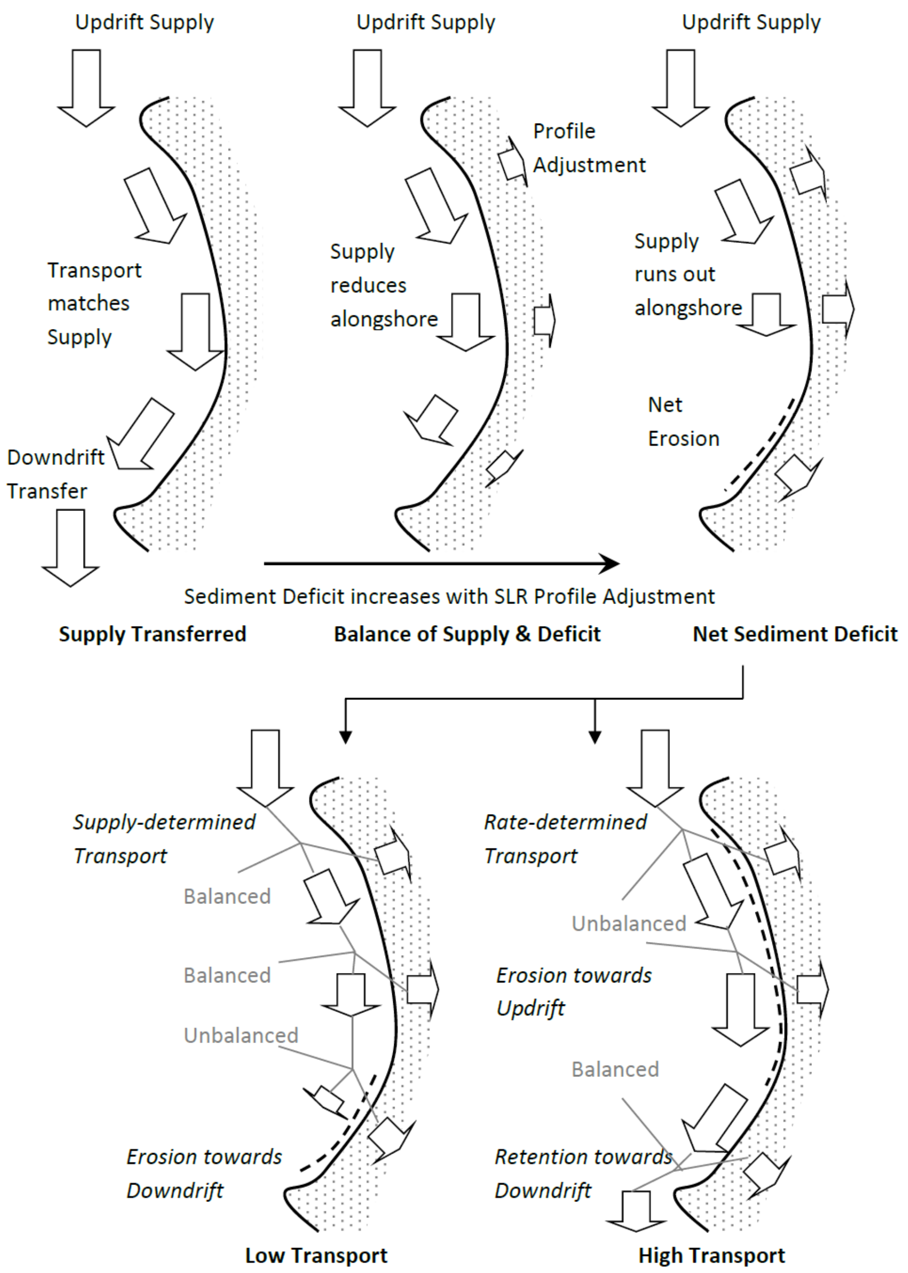


Figure 29: Effects of Sediment Deficit and Alongshore Transport Rate in an Open Sediment Cell

[e] Sediment demand is the rate at which sediment will tend to migrate towards a landform element (e.g. dune) from adjacent landform elements (e.g. beach and nearshore) due to the relative configuration of these elements and the dynamic processes influencing transport. This is related to the concept of sediment deficit, which is a representation of how different the beach configuration is to a 'dynamic equilibrium', where the net transfer between landform elements is zero over a nominated timescale.

6.4. Pilbara Region

The Pilbara Region contains Australia's most significant economic zone, with the coastal region being extensively modified to provide export facilities for oil, gas, iron ore and other natural resources. The Pilbara coast exhibits complex behaviour relating to the supply of sediment from large river systems, with existing coastal landforms demonstrating divergent response to sea-level rise over the Holocene [179]. For some coastal areas, landform development failed to keep pace with inundation, causing coastal lagoons to develop, while other parts of the coast largely retained their position. Geomorphic frameworks are considered to be an appropriate means to investigate the Pilbara's complex coastal behaviour. The need to improve understanding of response to sea-level rise in the Pilbara is critical for the management of strategic facilities and the communities which support them.

6.4.1. Pilbara Region Morphology

The Pilbara coast is largely comprised of low-lying arid floodplain, flanking a broad continental shelf, dominated by meso- through to macro-tidal variation, with the occasional effect of severe tropical cyclones. These deliver floods and marine inundation events that impact on the landscape and drive geomorphologic change on a coast which has a complex array of ancient and modern landforms. Active sedimentary landforms abut and overlie a complex and old terrain cut into the hard-rock Archaean geology of the Pilbara Craton and more recently formed sedimentary rocks.

Coastal landforms, including river deltas and tidal flats, extend more than 2km inland for the majority of the Pilbara. The river channels, riverine outwash plains, river deltas, tidal flats, coastal dunes, cheniers and spits, wide subtidal terraces and extensive sand shoals of the coast are all subject to significant change under extreme meteorologic and oceanographic conditions. However, the nature of landform response varies according to the relative resistance of the coast, which is a combination of material types (geology, sediment type and presence of vegetation) and the coastal form (which may be plan form, profile, or configuration of landform elements). The factors of environmental forcing, materials and landform have considerable interaction, in which variation of one factor potentially changes the other two. In this context there is an apparent disconnection between the fixed geologic framework and unconsolidated inshore sediment bodies.

The Pilbara coast is an inherited coast, with many sedimentary coastal landforms reflecting historic environmental conditions, millennia or centuries before present. Its ancient hard-rock terrain is overlain or abutted by sediments from coral reefs, floodplains and river deltas deposited through multiple phases over millions of years. In places the riverine sediments have been lithified, which along with old reefs and beachrock, now form coastal limestones.

River systems provide an important contribution to active coastal dynamics in the Pilbara Region through the episodic release of massive quantities of sediment. The largest Pilbara rivers are the De Grey, Ashburton and Fortescue Rivers. Not all streams and rivers discharge directly into the ocean, with many releasing water and sediments into tidal-flat basins that occur landward of the coastal ridge. However, these systems are connected to the coast via tidal creeks and irregularly contribute sediment to the coast at times of flood. While much of the released material is fine, and is broadly dispersed, the coarse fraction allows formation of deltaic features on the larger river systems and may contribute to sediment fans on the inner shelf [180]. In addition to sediment deposition from larger rivers, smaller stream systems and tidal channel networks interact within the broad areas of tidal flats prevalent along the Pilbara coast. These areas display the majority of inter-tidal and supra-tidal coastal change, with rapid switching between accretion and erosion of the tidal flats indicating adjustment to changing meteorologic and oceanographic conditions [181].

The geographic distribution of the rivers and their intermittent flow, results in sediment availability along the coast being extremely variable. Where sediment supply is limited, coastal variability is largely constrained by the rock framework and old landforms forming its inherited structure. Conversely, for areas of the Pilbara coast where sediment supply is effectively unrestricted, landform changes are highly variable and readily adjust to fluctuations in coastal processes.

The presence and nature of sedimentary features are highly variable across the broad and shallow shelf. These generally occur as shallow features overlying rock platforms, structurally constrained by retention or shelter from chains of limestone ridges and islands, many of which are remnants of previous shorelines. The nature of sheltering or retention may be significantly disturbed during tropical cyclones, causing a large shift in structure, which gradually returns towards the previous state under less energetic conditions. The nature of this cycle has been inferred from management of Port Hedland's shipping channel: significant sedimentation was not identified immediately after tropical cyclone impact, but elevated sedimentation rates were observed for several years following, gradually declining, and with winnowing of surface sediments measured [182,183,184].

Coastal dynamics in the Pilbara are brought about through an irregular combination of tidal flows, episodic tropical cyclone impacts, variable sediment release from river systems and generally mild ambient wave conditions [185]. These diverse environmental conditions produce change that is rarely responsive to a single forcing mechanism, with many sedimentary features in the Pilbara displaying perturbation-recovery behaviour. The large range of both tides and cyclone-induced waves means that many sedimentary coastal features are capable of being heavily eroded over short timeframes. However, the underlying or abutting geological framework may provide a physical limit to change. Hence, sedimentary features in the Pilbara tend to fall into the following classes:

- *Supply maintained features*, including deltas and strandplains, that have sufficiently high sediment supply that they are able to maintain a permanent presence;
- *Ephemeral features*, including spits, bars and beach 'ribbons', which experience periods of declined supply of enhanced erosion sufficient to cause short-term loss, with subsequent rebuilding;
- *Controlled features*, such as perched beaches or zones of updrift detention, where there is structural control that prevents the total disappearance of a feature, even under severe conditions;
- *Uncontrolled features*, including sand sheets, where neither supply nor structural control are sustained. These features may be formed due to a single event such as a tropical cyclone, and progressively evolve.

The distribution and relative permanence of sedimentary features is strongly linked to the proximity to river systems and their rate of sediment release [186]. Estimates of river system sediment delivery to the coast are not yet reliable [187,188], with the proportions of fine or coarse sediment and the estuarine structure having a significant influence on sediment fate as plumes or deposition.

6.4.2. Pilbara Coastal Energetics

Energetics potentially driving sediment transport across the Pilbara shelf are complex. The role of wave energy increases towards the shore and on the seaward side of ridges. Tidal currents change in direction and increase speed offshore, with localised areas of focusing where rock features (islands or ridges) provide restrictions. Connection between the shelf and inshore zones occurs intermittently through sand sheets or more extensive tidal structures such as the massive ridges offshore from Port Hedland (see Figure 31). The relative tendency for landward nearshore transport during ambient conditions is displayed by the formation of sand ribbons fronting low rocky cliffs, which are often overlain by perched beach and dune systems.

Despite the complexity of the geological framework and sediment transport energetics, the nature of nearshore sedimentary features indicates a spatial sequence of wave and current forcing (see Figure 30, Table 2). The corresponding change to seabed formations demonstrates the offshore transition from wave to tidal dominance (see Figure 31). Changes in the advective and dispersive nature of seabed sediments at Port Hedland is further illustrated by the movement of dredge spoil deposits, including landward movement of the spit adjacent to the shipping channel [189]. The spatial extent and speed of currents varies over time and with bathymetric structure. This determines that the zones are not fixed or wholly distinct, allowing direct connection, often for limited durations, between wind, wave and tidally formed sedimentary features. A spatial parallel occurs in locations where tidal currents may be high close to the shore, enabling interaction of forcing mechanisms. This occurs where deep water is close to shore, particularly along cliffs, or through exchange with tidal networks, including nearshore channels, tidal creeks and tidal flats.

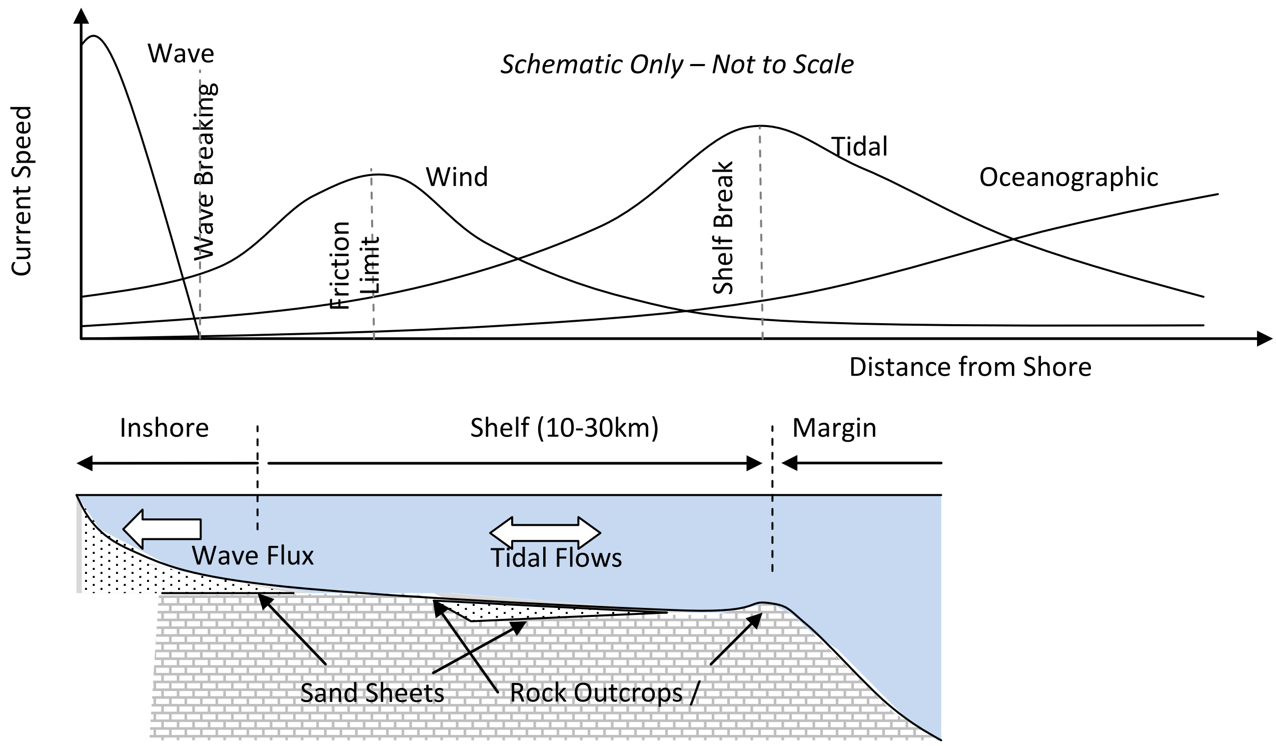


Figure 30: Pilbara Shelf Transport Zones

Table 2: Indicative Spatial Variation of Current Mechanisms

Location	Driving Process	Primary Direction	Description
At the Shore	Waves	Alongshore	Radiation stress
Nearshore	Waves	Onshore	Orbital residual
Inshore	Winds	Alongshore	Deflected by surface gradient (surge)
Mid-shore	Winds	Variable	Inertial response
Inner Shelf	Tides	Basin Determined	Influenced by bathymetry
Mid-shelf	Tides	Cross-shore	Peaks at top of shelf break
Outer Shelf	Oceanographic[f]	Alongshore	Increases off shelf edge

The onshore transport of material within the nearshore zone is an important factor in the formation and post-erosion recovery of coastal sedimentary features. For much of the Pilbara, coastal deposits occur as 'sand ribbons' on the seaward side of rock ridges, with extensive, flat sandy deposits in the nearshore. The low elevation of the coastal features implies that wave-driven recovery is incomplete, which in turn suggests that transport from the nearshore, determined by sand dispersion from tidal currents, acts to limit the delivery rate.

[f] Shelf-edge currents typically generated by steric gradients, including the Leeuwin Current and more short-lived phenomena.

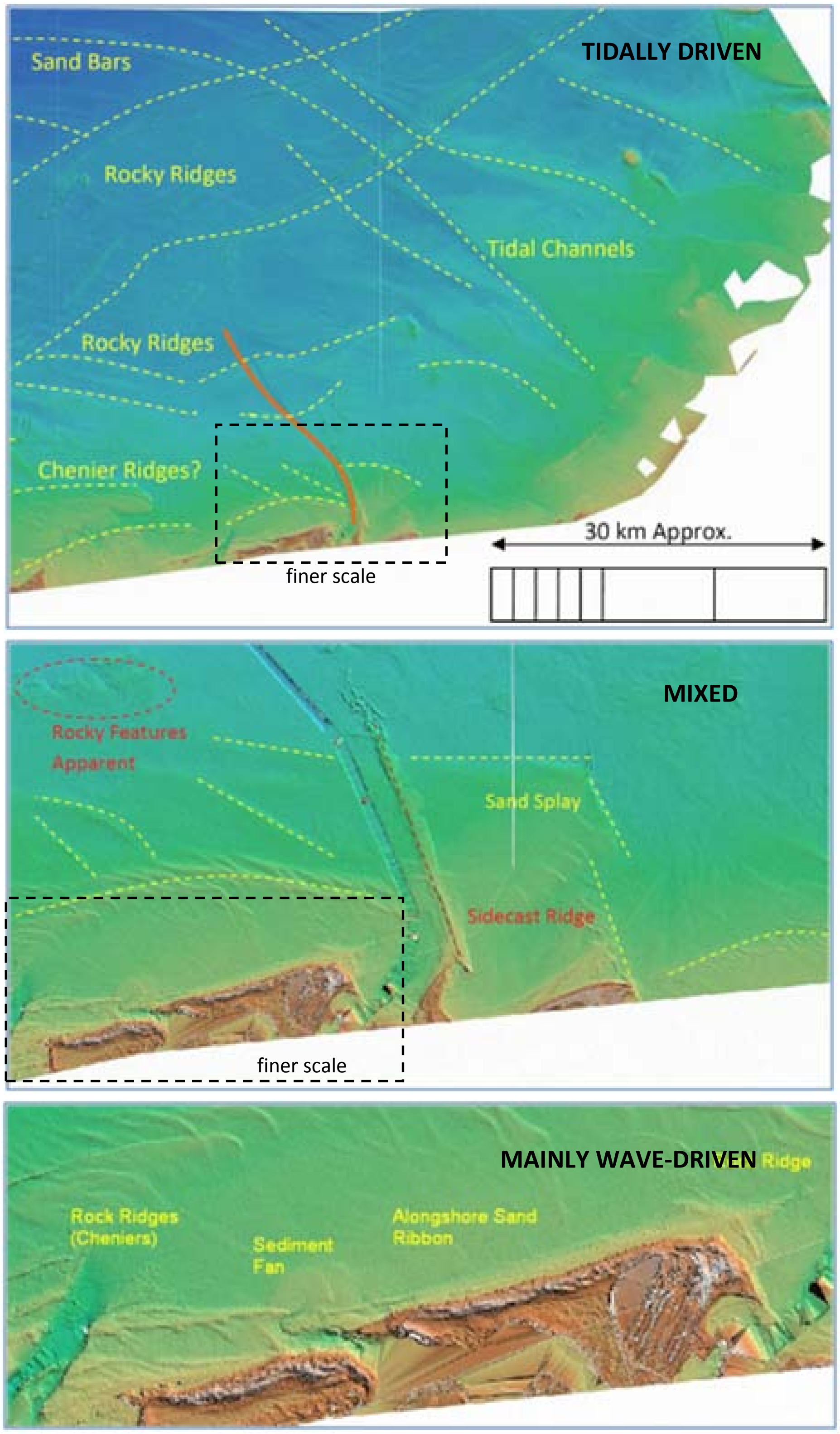
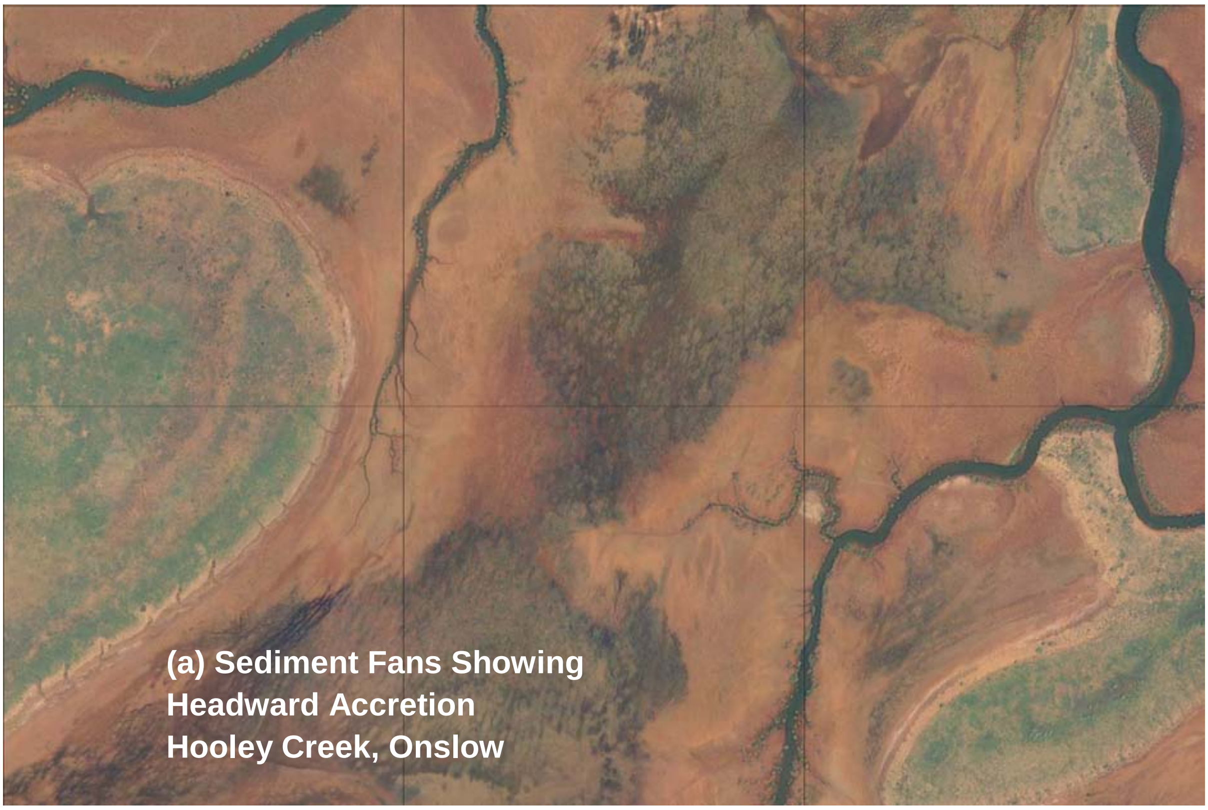


Figure 31: Nature of Seabed Features Changes with Scale at Port Hedland From Eliot (2010)[184]

Exchange between the coast and tidal networks provides a major pathway for sediments. This may be predominantly outgoing for deltas and incoming for estuary basins [190]. However, for the tidal flats prevalent along the Pilbara coast, rapid switching between erosion and accretion at the headward limit of tidal creeks indicates ability to either import or release sediment in response to changing conditions (see Figure 32).



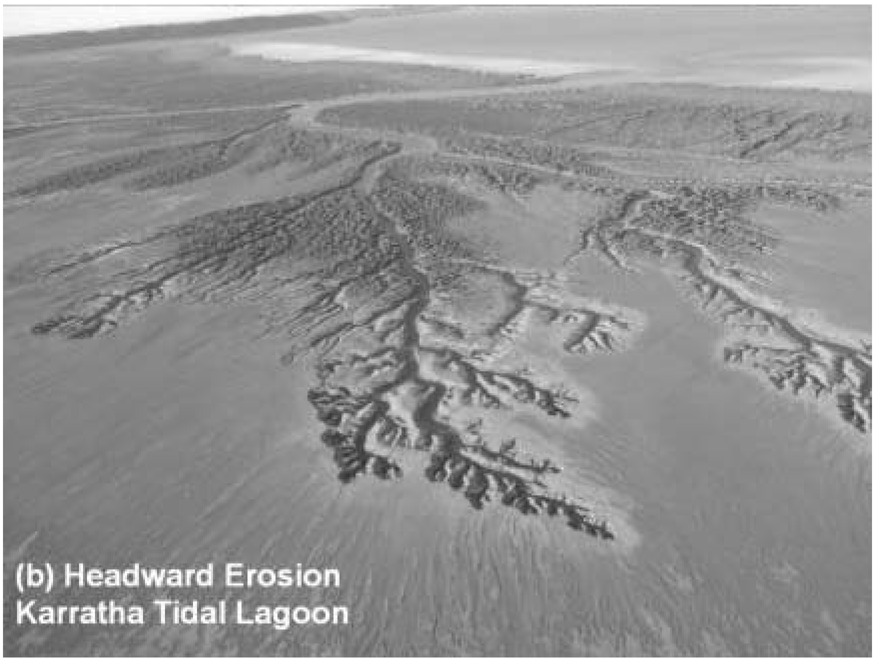
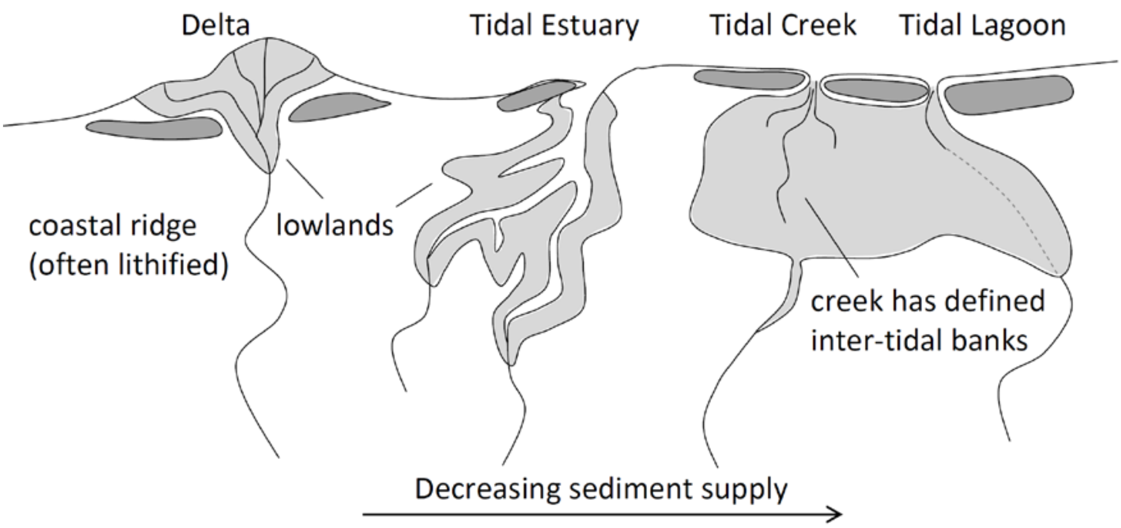
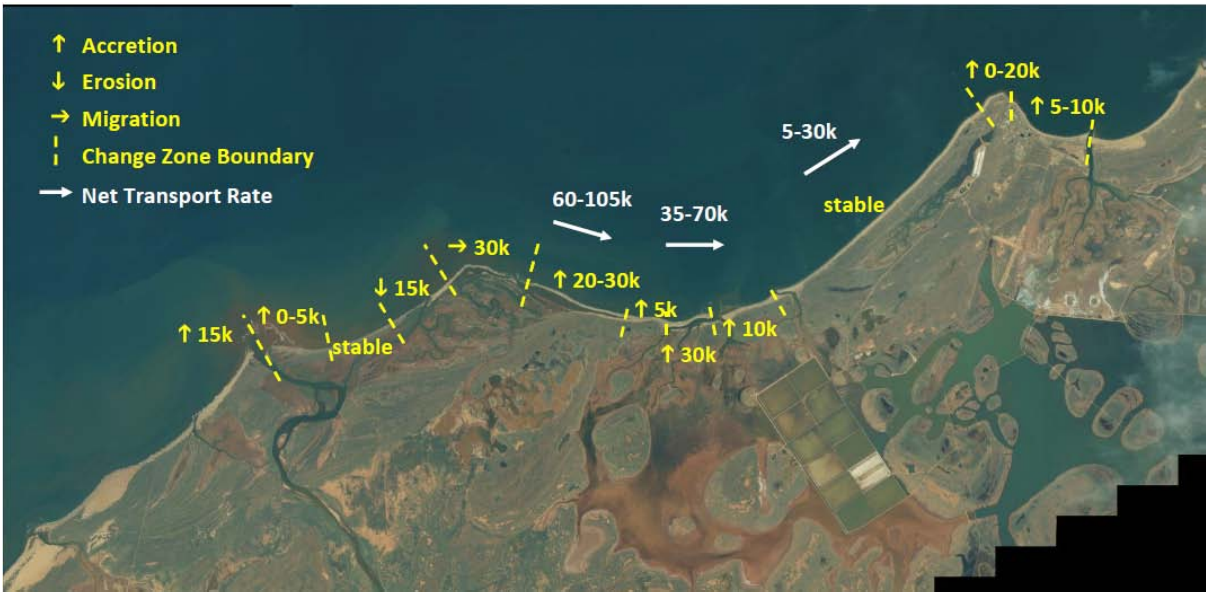


Figure 32: 'Snapshot' Interpretation of Depositional or Erosive Tidal Creek Behaviour From Eliot & Eliot (2013)[181]

The mechanism of tidal flat adjustment has been argued as a major factor in coastal evolution across the Pilbara [179]. When combined with the influence of proximity to sediment supply, the observed geomorphic progression (see Figure 33) suggests that coastal wetlands and tidal flats may potentially have alternate pathways that either keep pace with sea-level rise, or experience drowning, shifting a tidal flat towards a tidal lagoon.



(a) Conceptual relationship between supply and estuary form



(b) Notional sediment budget derived from surface features near Onslow

Figure 33: Conceptual and Actual Progression of Estuarine Form within a Sediment Cell Extract from Eliot & Eliot (2013) [181]

Due to the presence of tidal flat systems along the majority of the Pilbara coast, the likely coastal response to sea-level rise should incorporate a conceptual model of shore–estuary sediment transfer [191]. This may require tidal channel energetics to adequately describe sediment distribution within the estuary[192,193]. The more widely applied conceptual model of shore–shelf sediment transfer may also be appropriate, although this should apparently incorporate tidal, wind and wave-driven energetics, and is likely to result in a limited proportion of infilling across the shelf area. For areas where sediment delivery to the estuary is mainly marine [190], then the role of alongshore sediment transport is likely to be enhanced. The sediment deficit caused by sea-level rise will therefore affect the sediment budget, with greater downdrift impacts within a sediment cell. This highlights the importance of considering change within a compartmentalised framework. For deltas and estuaries where there is a high fluvial sediment supply, there is increased opportunity for the sediment deficit to result in vertical floodplain growth, although this may occur as a series of embankment breaches, or a more even progression [194,195,196].

The patterns of behaviour described above provide a highly simplified explanation for the general manner in which the Pilbara coast operates. Important aspects are the capacity for both fluvial and marine mechanisms to supply sand to the coast, along with the potential transfer from offshore sand sheets towards shore. The sand sheets themselves are largely relicts pre-dating the Holocene stillstand including palaeo-deltas, although there are occasionally more modern deposits overlying Pleistocene limestone features [197].

Use of geomorphic frameworks when assessing likely coastal response to sea-level rise in the Pilbara have either been qualitative [179] or applied to a relatively confined cell [198]. However, the ability of the sediment budget approach to help explain the spatial variation of landforms and the observed patterns of coastal change suggest that geomorphic frameworks may be a valuable tool in the Pilbara, provided suitable refinement to incorporate tidal and floodplain effects. Key differences from the conceptual cross-shore balance model (see Figure 6) that have been interpreted from coastal observations and stratigraphic investigations in the Pilbara are: the bi-directional role of onshore impoundment; the influence of coastal compartmentalisation; and the ephemeral (seasonal to sub-decadal) nature of sediment storage associated with intermittent (typically decadal or longer) delivery of river sediments (see Figure 34).

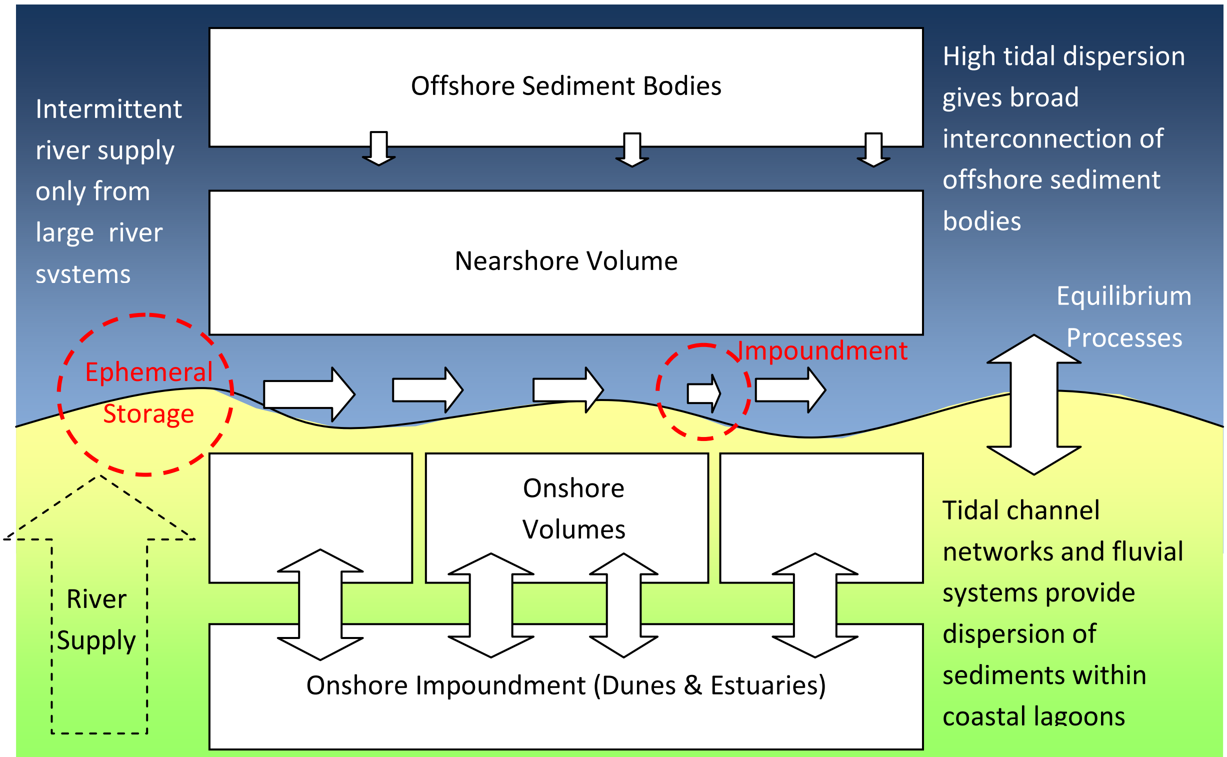


Figure 34: Schematic Behaviour of Pilbara Coast

7. Synthesis of Previous Studies

Current 'best practice' for sea-level rise impact assessment [36,134]:

- Considers change to meteorologic and oceanographic conditions (sea-level and storminess);
- Evaluates a shift of equilibrium profiles;
- Assesses erosion and potential destabilisation caused by storm events;
- Incorporates sediment demand associated with coastal wetlands and tidal inlets; and
- Determines potential for overwash and instability on coastal barriers.

Ultimately these processes provide fine-resolution information regarding coastal change and do not address the volume of shore–shelf or shore–floodplain sediment exchange. Techniques for these broad-scale mechanisms of change vary considerably, but use of the simple Bruun rule is common, regardless of its validity. Within either framework for sediment exchange, material is transferred from one eroding geomorphic unit towards another accreting geomorphic unit. The pathway by which this transfer occurs may restrict the effectiveness of exchange and therefore is of enormous importance to the question of coastal response to sea-level rise.

Simple models for shore–shelf sediment exchange are largely based upon geometric response within the accreting geomorphic unit (the inner shelf) and a corresponding change to the coastal area, with a net zero supply. Alternative models for change variously assume constant, linear or exponential infill across the area proportional to sea-level rise (see Figure 35), with the latter following the geometry of theoretical beach profile equilibrium[199]. Choice of a constant infill model will give coastal recession approximately 400% larger than exponential infill, and consequently model choice may dramatically affect the projected coastal change. The effect of a net sediment supply will also reduce the effective 'demand' imposed on the eroding shore. Under present-day conditions, there is positive sediment supply to both the Vlamingh and Pilbara Regions mainly from alongshore and fluvial sources respectively, which may effectively dampen response to sea-level rise (see Figure 35). However, under projected longer-term conditions, the cumulative demand along connected reaches of coast will reduce reliability of sediment supply towards the updrift end of sediment cells, therefore increasing the relative proportion of infill that is fed by shore–shelf sediment transfer towards the downdrift end of the cells.

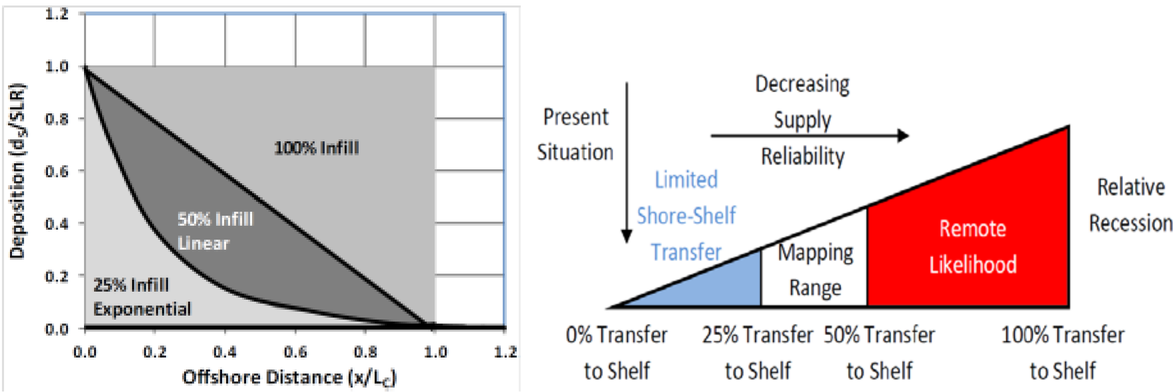


Figure 35: Relative Efficiency of Shore–Shelf Transfer

Analysis of the seabed formations throughout the Vlamingh and Pilbara Regions challenges use of the generally applied conceptual model of cross-shore balance. Comparison of landforms has demonstrated systematic discrepancies to alongshore patterns of change, the role of rock formations and the capacity for landward sediment transfer through tidal networks. Coastal compartmentalisation enables steeper gradients of alongshore transport to occur, and therefore may significantly increase the role of alongshore supply.

Landform analysis clearly demonstrates that coastal evolution and development is not homogeneous. Evaluation of bedforms and sandbars in both the Vlamingh and Pilbara Regions suggests that onshore sediment transfers are indirect and typically involve a secondary process, such as tidal flow. For many locations, onshore sediment supply is provided by discrete feeds, particularly through gaps in reef systems. Delivery rates through these pathways are not apparently related to the depth of closure concept, and it is appropriate to consider in detail the energetics (waves, currents, turbulence) of these pathways when assessing potential rates of shore–shelf exchange. A key implication is that transfer of material to offshore is not the same mechanism as the transfer of material onshore. For complex seabed conditions, this means that the relative efficiency of shore–shelf transfer is likely to be reduced.

The role of coastal rock formations is particularly important for the relative distribution of sediment, and therefore an important aspect when considering downscaling of sediment budgets. It is suggested that compartmentalised coasts require additional consideration to:

- Identify net sediment budget;
- Assess the stability of available sand feeds;
- Determine alongshore transport rates and bypassing around coastal restrictions;
- Evaluate sediment transfer and capacity for impoundment (in both longshore and cross-shore directions) and
- Establish how behaviour may change with sea-level and coastal recession.

These characteristics are important to provide downscaling of information to a suitable scale for consideration of engineering works. Existing landforms and modern behaviour in response to interventions suggest that the internal distribution of sediment, and therefore focal zones of erosion, is likely to be affected by internal sediment transfer patterns (i.e. may affect disaggregation when downscaling). Without suitable downscaling, aggregated models for change generally provide a poor representation for the purposes of adaptation planning, and essentially only provide an indication that being closer to the shore is a position of greater hazard.

The role of nearshore rock, including subtidal features, is poorly represented within modelling, and suggests behaviour counter to landform evidence. An example is presented in the Vlamingh Region, near the mouth of the Capel River (see Figure 36). The width and elevation of the nearshore rock platform is strongly related to the height of the coastal dune system, suggesting that there is less capacity for material to be exchanged offshore.

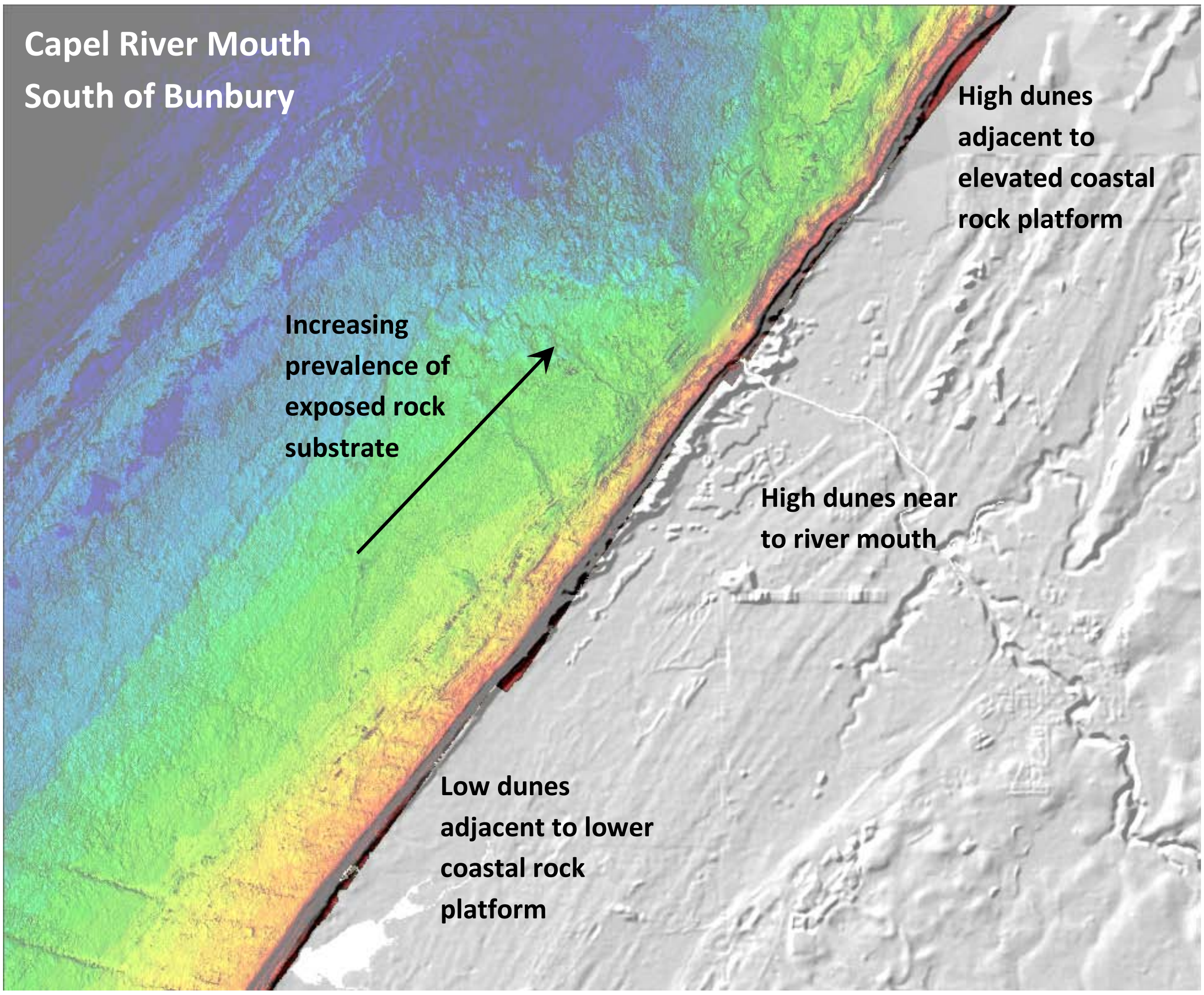


Figure 36: Larger Dunes Associated with Broader Subtidal Rock Platform
Imagery from Bob Gozzard, Geological Survey of Western Australia

8. Applications of Geomorphic Frameworks

Geomorphic frameworks provide a potential tool to advance the assessment of sea-level rise impact on the Australian coast. Suitable use of the frameworks provides a means of capturing the complexity of coastal behaviour at multiple scales, and therefore a better representation of response to change. Through the use of a hierarchical framework, it is possible to relate behaviour from sparse observations through upscaling and downscaling, thereby providing a cost-effective use of coastal data collection.

Recent advances in technology and science have dramatically improved capacity to use geomorphic frameworks effectively. These include high-resolution capture of seabed structures through remotely sensed techniques such as LiDAR and LADS, along with a deeper understanding of the connectivity between coastal land systems and landforms.

In general terms, at the largest scales of evaluation, geomorphology should define the selection of major model processes suitable for assessment of coastal change. Coastal sediment cells, within which there is a high degree of connectivity, should be used to define spatial scales of assessment. At an even finer scale, landforms provide the building blocks within which sediment exchange may occur. Notably, sediment cells need not be wholly closed coastal units, and connectivity between sediment cells should be used to determine the relative distribution of alongshore sediment supply, and the consequent effect of sediment deficit caused by sea-level rise.

Evaluation of behaviour within the Vlamingh and Pilbara Regions of Western Australia has demonstrated complex coastal responses, indicating the need for integration of multiple scales of change when evaluating potential coastal change due to sea-level rise. The compartmentalised nature of these coastal regions enhances the importance of alongshore sediment transport, and it is recommended that sea-level rise impact assessment should consider application of geomorphic frameworks to project potential sediment budget changes. Further downscaling to an engineering scale is necessary to make this useful for adaptive decision-making, which requires consideration of relative sediment distributions inside sediment cells.

Appendix A Revisiting Landforms in Coastal Engineering

Eliot MJ, Stul T & Eliot IG. (2013) *Revisiting Landforms in Coastal Engineering*. Coasts and Ports 2013 Conference Proceedings.

Appendix B Coastal Compartments of Western Australia: A Physical Framework for Marine & Coastal Planning

Eliot I, Nutt C, Gozzard B, Higgins M, Buckley E and Bowyer J. (2011) *Coastal Compartments of Western Australia: A Physical Framework for Marine and Coastal Planning*. Report 80-02. Damara WA Pty Ltd. Report to the Departments of Environment and Conservation, Planning and Transport. Environmental Protection Authority.

Appendix C WA Coastal Sediment Cells
Coastal Sediment Cells between Cape Naturaliste and the Moore River, Western Australia

Stul T, Gozzard JR, Eliot IG & Eliot MJ. (2012) *Coastal Sediment Cells between Cape Naturaliste and the Moore River, Western Australia*. Report prepared by Damara WA Pty Ltd and Geological Survey of Western Australia for the Western Australian Department of Transport, Fremantle.

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