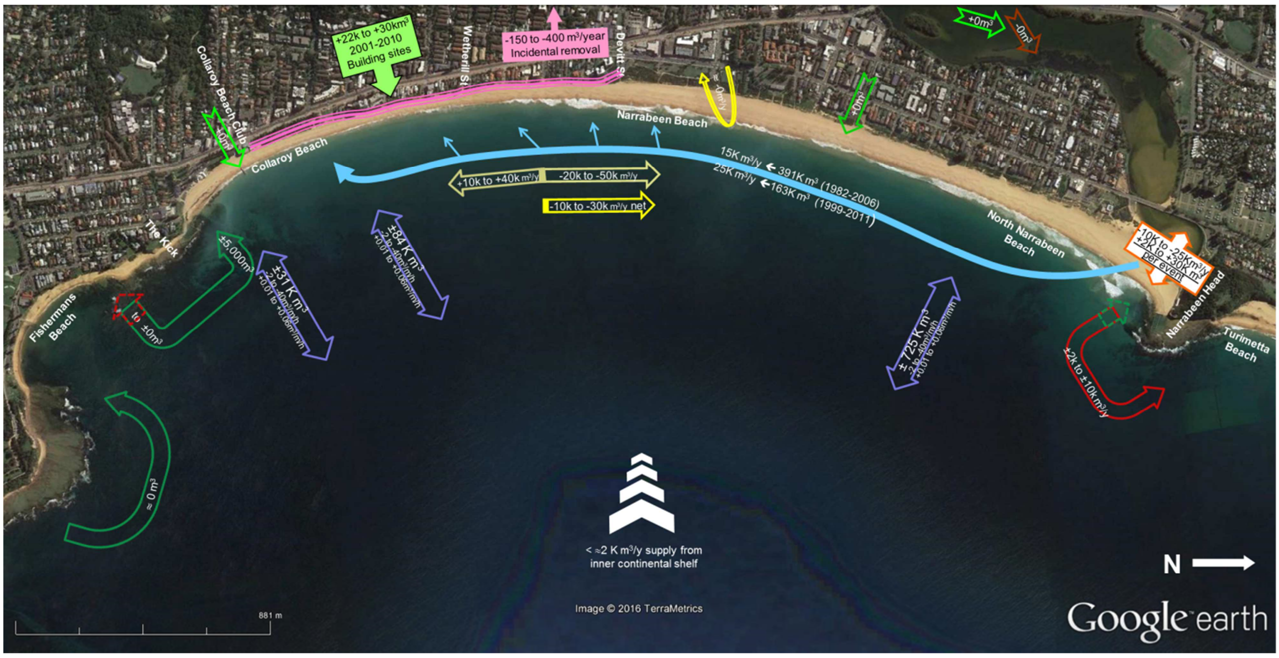
Manly Hydraulics Laboratory

COLLAROY-NARRABEEN BEACH COASTAL PROTECTION ASSESSMENT



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Cover Photograph: Quantitative Coastal Processes Model for Collaroy-Narrabeen Beach

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Foreword

NSW government's professional specialist advisor, Manly Hydraulics Laboratory (MHL) in association with the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Australia were commissioned by Northern Beaches Council (NBC) to review the concept design and concept alignment of the proposed coastal protection works for Collaroy-Narrabeen Beach, south of Devitt Street Narrabeen. The review includes an analytical assessment of the relative impacts on coastal processes within the Collaroy-Narrabeen Beach embayment.

The report was prepared by James Carley (of WRL), Ed Couriel and Galen Lewis (of MHL).

Executive Summary

Collaroy-Narrabeen Beach is characterised as having the most highly capitalised shoreline in Sydney's Northern Beaches and is also classified as the most at risk from coastal processes in NSW and the third most at risk nationally. The main cause of the existing coastal hazards is that development has taken place well within the active coastal zone (within the primary foredune area). The Coastal Zone Management Plan (CZMP) for Collaroy-Narrabeen Beach and Fishermans Beach was adopted by Council in October 2014 and certified by the NSW Government in November 2015. This Plan recognises the need to protect and preserve the amenity and natural values of Collaroy-Narrabeen Beach and recognises that properties adjoining the beach have been adversely impacted by severe coastal storms in the past and are presently exposed to coastline hazards.

The CZMP recognises also that existing protection works have been constructed in an ad-hoc manner and have generally been undertaken without comprehensive engineering design. For management of the coastal erosion hazard, the only location where coastal protective works by property owners are considered to be necessary and suitable (provided they manage any offsite impacts and subject to the requirements of the Environmental Planning and Assessment Act 1979), is south of Devitt Street (**Figure A**). Protective works at other locations are not considered necessary or suitable at this time.

Northern Beaches Council engaged an Engineering Consultant (Royal HaskoningDHV) to prepare a concept design and conceptual alignment for about 1,350 m of improved protection works from the north-east corner of the Collaroy Services Beach Club (chainage; Ch 0 m) in the south, up to Devitt Street (Ch 1,337 m) in the north. The proposed coastal protection improvement works are to be designed and constructed for design conditions with a minimum Average Recurrence Interval of 50 years and a design life of at least 60 years.

The NSW government's professional specialist advisor, Manly Hydraulics Laboratory (MHL) in association with UNSW Australia's Water Research Laboratory (WRL) were engaged by Northern Beaches Council to review the concept design and concept alignment of the proposed coastal protection improvement works and to assess their expected impacts on coastal processes and beach amenity relative to the present situation. The methodology adopted, findings and recommendations arising from that review are summarised below.

This assessment of the proposed coastal protection improvement works has been based on a comparison with the current foreshore state, inclusive of the existing ad-hoc protection works, their present impacts (which have existed for several decades) and ongoing sand management practices. It has drawn upon the present understanding of existing coastal hazards and a quantitative coastal processes model (**Figure A**), which has been developed from existing relevant data and studies.

To best understand the present day coastal processes operating along Collaroy-Narrabeen Beach, it is important to understand the geological history of the NSW coastline, the broader regional scale sediment dynamics and the key physical processes responsible for the present form of the Sydney Northern Beaches Coastal Sediment Compartment, the wider

Sydney Primary Coastal Sediment Compartment (see **Figure 1**) and the Collaroy-Narrabeen Beach Sub-Compartment (see **Figure 2**).

Sydney's beaches are characterised by a series of prominent outcropping headlands which largely contain sediments within these major features. Only following rare and sporadic major or extreme coastal storms, which are able to transport sediments sufficiently offshore, do littoral sediments bypass these headlands to neighbouring compartments via onshore transport under calmer shore oblique waves. The sandy beaches along Sydney's Northern Beaches are dynamic with erosion events, but are generally stable over the long term.

The main physical coastal processes (erosive and accretionary) relevant to Collaroy-Narrabeen Beach have been summarised using a Quantitative Coastal Processes Model as illustrated in **Figure A**, and summarised below using the following sediment budget related colour coding:

- ⇨ Sediment budget process sources (additions) are depicted as **+bold green**;
- ⇨ Sediment budget process sinks (losses) are depicted as -underlined red; and
- ⇨ Balanced or neutral sediment budget processes are depicted as *italic grey*.

- Inner Continental Shelf interaction (**< approx. +2,000 m^3/y**);
- Net longshore sediment transport (-10,000 to -30,000 m^3/y; mostly into lagoon);
- Lagoon entrance dynamics (see *longshore transport and entrance management*);
- Cross-shore sediment transport (< *approx. ±840,000 m^3*);
- Headland bypassing (**+0 m^3/y @Long Reef Point**, *±2,000 to ±10,000 m^3/y @Narrabeen Head* and <approx. -2,000 m^3/y @Turimetta Head);
- Fluvial sediment inputs and deposition (*approx. ±0 m^3/y*);
- Aeolian transport (*approx. ±0 m^3/y*);
- Entrance management (**+15,000 to +25,000 m^3/y** anthropogenic sand recycling);
- Building sites (**+2,000 to +3,000 m^3/y** anthropogenic sand nourishment);
- Incidental Removal (-150 to -400 m^3/y anthropogenic); and
- Sand grain size abrasion and headland weathering (*approx. ±0 m^3/y*)

The above sediment budget indicates that onshore transport of inner-shelf sand, although small in the scale of other cross-shore and longshore processes, has the potential to balance the expected long-term sand losses attributable to post storm headland bypassing and potentially also to assist natural beach transgression in response to present and projected future sea level rise. There is no evidence that Narrabeen Lagoon or the existing stormwater drains provide any significant net contribution of sand sized material to the beach and the only relevant interaction between the Lagoon and beach sediments is associated with the flood tide delta (a temporary sediment sink – see **Figure A** and Lagoon entrance dynamics above). No significant net loss of sand from the beach occurs by aeolian processes as Council periodically sweeps this material back onto the beach.

The careful management of the lagoon's entrance (by recycling sand every 3 years to 5 years) and the extra sand nourishment from building sites (averaging 2,000 to 3,000 m^3/y) have helped maintain and even prograde the finely balanced sediment budget of Collaroy-Narrabeen Beach.

Because the Collaroy-Narrabeen Beach embayment is essentially a stable closed system, the most significant processes in terms of beach fluctuations and shoreline alignment are cross-shore and longshore sediment transport, including the alongshore variability in onshore and offshore sand movements and the time expected for beach recovery following major storms.

Rapid rates of offshore sand transport are experienced during storms, ranging from -2 m^3/m/hour to -40 m^3/m/hour above AHD. Beach recovery rates are much slower, typically ranging from +0.01 m^3/m/hour, up to +0.06 m^3/m/hour (equivalent to approximately 0.2 m^3/m/day up to 1.5 m^3/m/day). These rates correspond to complete beach erosion taking place over a matter of hours or days and beach recovery typically taking place over 3 months to two or more years. Despite its significant effects, it is noteworthy that the June 2016 storm event was characterised by a total erosion volume (400,000 m^3) of less than half of the upper bound limit of storm demand that could occur for a series of successive multi-directional storms. For this event, the eroded beach is expected to recover in no less than 90 days and over as much as about 640 days based on historically recorded beach recovery rates.

The quantitative review undertaken in this study of the Collaroy-Narrabeen Beach coastal processes validates the contemporary understanding that the main cause of the existing coastal hazards is that development has taken place within the active coastal zone. The process understanding developed provides some confidence to the assessment of the likely impacts of the proposed coastal protection improvement works on the coastal processes and beach amenity of the study area.

The concept design cross-sections and alignment for the proposed coastal protection improvement works are expected to result in completed works with a footprint that is generally landward or at most, within +2 m to +3 m seaward of the existing ad-hoc works. The representative rock armour concept design cross-sections are expected to be completely buried by beach sand under typical (non-eroded) beach states. The adopted 6 m maintenance corridor along the crest is considered to be a suitable distance, although this could potentially be reduced to 4.6 m and still provide satisfactory access based on Gold Coast experience. More landward alignments than this are not considered practicable given existing building lines.

A minimum design crest level of 6.5 m AHD should be adopted for conventional rock rubble mound armour designs to satisfy EurOtop (2007) recommended average wave overtopping limits, including consideration for future sea level rise and allowing for some albeit minor damage to foreshore areas, dwellings and infrastructure. Higher minimum seawall crest elevations are likely to be required for alternative and/or composite seawall designs, where vertical or impervious elements are included. Lower initial design crest levels could be adopted where adequate allowance is made for future raising of the crest to adapt for sea level rise projections given that development types and setback distances vary, and the existing foreshore elevation varies from about +4.5 m AHD (towards the south) to above +7.0 m AHD (in the north).

The proposed works south of Devitt Street are considered to be in general compliance with the requirements of the certified CZMP (2014) and the Draft Northern Beaches Coastal

Erosion Policy. It is noted, however, that proposed funding arrangements, detailed design, development consent, sand offsets, construction and maintenance aspects of the CZMP (2014) and Coastal Erosion Policy are not evaluated as part of this assessment.

With regard to public access arrangements, it is considered that ongoing maintenance of existing access paths, beach scraping, fencing and appropriate signage following storm erosion (consistent with Council's existing practices) are appropriate. Ongoing sand recycling from the lagoon entrance and sand nourishment from suitable building sites, as proposed, are both also strongly supported. Additional large scale sand nourishment by government to mitigate possible beach recession effects associated with projected sea level rise is generally supported as a viable management response should this prove to be necessary.

The visual amenity of the proposed concept design is expected to be effectively unchanged most of the time when the proposed improvement works are buried in sand. Following storms, the visual amenity would be improved in terms of uniformity of appearance, access and public safety. It is concluded that the overall visual impacts compared with the status quo will be positive.

The proposed coastal protection improvement works will be designed and constructed to accepted engineering standards, and while some damage may still be expected during major coastal storm events beyond the adopted design conditions, this is expected to be in a far more controlled and acceptable/planned manner. The proposed coastal protection improvement works, therefore, are expected to provide improved public access and vastly improved serviceability and public safety (removing overhangs and rocks strewn on the beach) with the proposed alignment established to maximise the public beach amenity as far as practicable in comparison to the existing ad-hoc works.

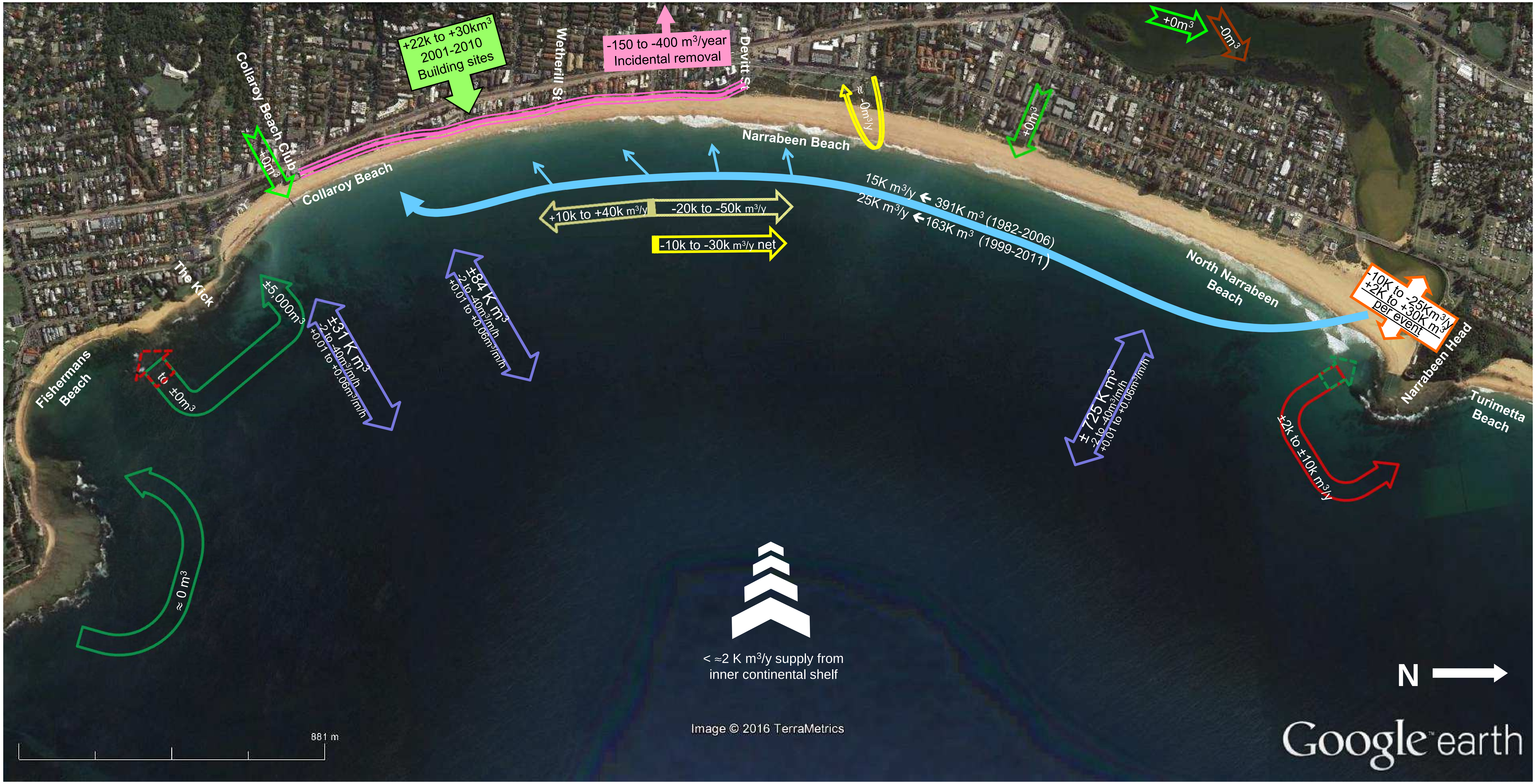
The overall finding of this review of the proposed coastal protection improvement works for Collaroy-Narrabeen Beach is that no discernible adverse impacts have been identified on existing coastal processes or amenity values compared with the existing situation. The overall benefits of the proposed coastal protection improvement works in terms of satisfying contemporary serviceability levels with regards to coastal protection and vastly improved public safety have also been discussed.

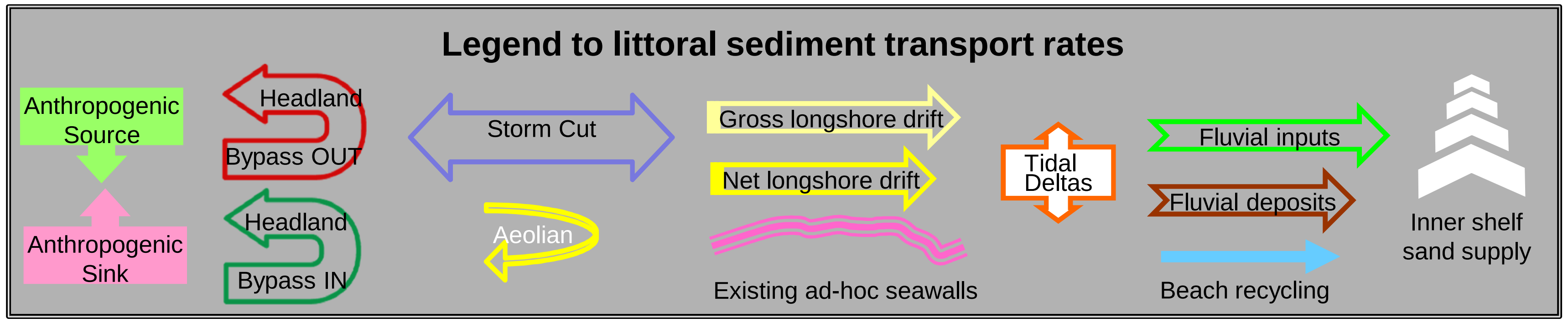
It is recommended generally that the proposed coastal protection improvement works be aligned as far landward as practicable. Based on a preliminary and approximate only analysis, an alignment tolerance of no more than about +2 m seaward of the existing ad-hoc works is recommended, based on this resulting in no expected discernible incremental impacts on alongshore beach access relative to the status quo. Seaward projections of more than +2 m are expected to cause significant increases in the amount of time the beach would be impassable based on this preliminary evaluation. A more detailed probabilistic approach, involving a full time-series simulation of wave run-up levels incorporating a representative long-term historical period of measured ocean water levels and waves is strongly recommended. This more realistic analysis would provide the expected percentage of lost amenity time for different seawall alignments, and could potentially indicate an alignment more seaward than +2 m to be acceptable for some locations.

It is recommended also that all existing sand management practices comprising entrance sand recycling and building site sand nourishment be continued. Additional large/regional scale sand nourishment should be pursued if a need or cost effective opportunity arises.

Other recommendations arising from this review relating to the detailed design of the proposed coastal protection improvement works comprise:

- taking into account sensitivity analysis of the design nearshore water level based on wave setup, including the truncation of the surfzone with a seawall (and therefore the full quantum of wave setup on a dissipative beach not being realised);
- the consequences of potential scour below -1 m AHD where it is physically possible;
- assessing the consequences of 1 hour duration design wave conditions in terms of checking the stability and expected damage to proposed improvement works;
- utilising the NSW nearshore wave transformation tool to check design wave conditions;
- taking into account storm wave overtopping discharge rates and local rainfall runoff drainage;
- checking site-specific factors when confirming the final design crest level, including the capability of the local drainage system, nature of buildings (value and construction materials) and proximity of these and other assets landward of the proposed improvement works – structures incorporating explicit design allowances and triggers for future sea level rise adaptation may be able to adopt lower initial design crest levels;
- physical model testing to verify wave overtopping rates, overall stability and the suitability of any proposed non-conventional rock rubble mound structures;
- provide more explicit guidance on correct granular filter layer, drainage and geotextile design to manage design wave overtopping rates and avoid excessive hydrostatic forcing, comprising a minimum width and depth of granular filter materials and geotextile details; and
- If Council were to allow any owners to rely on any existing coastal protection works, it is strongly recommended that a detailed condition assessment and design review report for the relevant existing structures be obtained from a suitably experienced coastal engineer.





NOTE – The coastline between Long Reef Point and Turimetta Head, including Fishermans Beach and Turimetta Beach (see **Figure 2**), form part of the Collaroy-Narrabeen Coastal Sediment Sub-Compartment. The complete sub-compartment has been omitted from **Figure 4** only for simplicity, noting primary interconnections are low and infrequent (north and southbound) between Fishermans Beach and Collaroy Beach and between Turimetta Beach and North Narrabeen (less than approx. ±2 to ±30,000 m³ pa on inter-annual/inter-decadal cycles; see Headland Bypassing arrows), with nil/negligible Headland Bypassing of Long Reef Point from the Dee Why – Long Reef Coastal Sediment Sub-Compartment.

Contents

TABLES

FIGURES 43

1. Introduction and Project Background

1.1 Background

Collaroy-Narrabeen Beach is one of the Northern Beaches Council's most significant natural assets and is highly valued by both residents and visitors to the Warringah area. Collaroy-Narrabeen is about 18 km northeast of the Sydney CBD (**Figure 1**) and the beach is about 3.6 km in length. It generally faces approximately east, facing east-south-east at the North Narrabeen end and east-north-east at the southern Collaroy end (**Figure 2**).

Collaroy-Narrabeen Beach is characterised as having the most highly capitalised shoreline in the Northern Beaches and is also classified as the most at risk from coastal processes in NSW and the third most at risk nationally. Collaroy-Narrabeen Beach has a history of ad-hoc emergency protection works being placed during and after coastal storms. Many of the ad-hoc works have been in place since the 1960s with ongoing repairs and/or ad-hoc or emergency augmentations following major coastal storms up to the present day. Although the degree of protection from coastal hazards offered by the existing ad-hoc structures is largely inadequate and highly variable along the beach, their impact on the day to day coastal processes and general beach amenity is well understood. The main cause of the existing coastal hazards being that development has taken place well within the active coastal zone (within the primary foredune area).

The Coastal Zone Management Plan (CZMP) for Collaroy-Narrabeen Beach and Fishermans Beach was adopted by Council in October 2014 and certified by the NSW Government in November 2015. This plan establishes a framework through which both beaches are managed for current and future generations.

While recognising the need to protect and preserve the amenity and natural values of Collaroy-Narrabeen Beach and Fishermans Beach, the CZMP also recognises that properties adjoining Collaroy-Narrabeen Beach have been adversely impacted by severe coastal storms in the past and are presently exposed to coastline hazards including erosion and inundation from wave overtopping. The only location where coastal protective works by property owners are considered to be necessary and suitable (provided they manage any offsite impacts and subject to the requirements of the Environmental Planning and Assessment Act 1979), is south of Devitt Street at Collaroy-Narrabeen Beach (CZMP, 2014). Protective works at other locations are not considered necessary or suitable at this time.

Between 4 and 6 June 2016, Sydney experienced an intense East Coast Low event that saw heavy rainfall with large ocean swells. This resulted in the significant erosion of Collaroy-Narrabeen Beach and caused damage to private/public property and infrastructure including houses, sewer lines, roads, and stormwater assets south of Devitt Street. The storm also exposed previously buried seawalls and exposed areas where no seawalls were present between Ramsay Street and Stuart Street.

In September 2016, Northern Beaches Council engaged an Engineering Consultant (Royal HaskoningDHV) to prepare a concept design and conceptual alignment for about 1,350 m of improved protection works from the north-east corner of the Collaroy Beach Club (chainage; Ch 0 m) in the south up to Devitt Street (Ch 1,337 m) in the north. Existing (albeit mostly inadequate) rock rubble mound seawalls already exist along most of this stretch of the beach, with about 110 m of unprotected foreshore between Ramsay Street (Ch 510 m) and Stuart Street (Ch 620 m) and about 40 m in total of vertical or composite seawall structures (at Ch 250 m and Ch 620 m). Wetherill Street (Ch 785 m), which delineates the boundary between Collaroy and Narrabeen, represents the most seaward position of the existing structures relative to the normal high water mark and is where the beach is narrowest under typical (not eroded) beach conditions.

Manly Hydraulics Laboratory (MHL) in association with UNSW WRL were subsequently engaged by Northern Beaches Council to review the concept design and concept alignment of the proposed coastal protection improvement works and to assess their expected impacts on coastal processes and beach amenity relative to the present situation. This Report outlines the methodology adopted and findings of that review.

1.2 Purpose and Scope

This review of the concept design and alignment for the proposed coastal protection improvement works at Collaroy-Narrabeen Beach is based primarily on a synthesis of the extensive existing relevant information and additional details provided by the Engineering Design Consultant and Northern Beaches Council during a series of focus meetings.

The main purpose of this review is to assess whether:

i) the long-term coastal processes of the Collaroy-Narrabeen Beach embayment are maintained compared with the existing state of coastal processes (already affected by existing ad-hoc seawalls of various construction materials and limited design standards) – the evaluation is focused particularly on how the proposed coastal protection improvement works are expected to interact with the coastal processes compared with how the existing seawalls interact;

ii) the proposed coastal protection improvement works are situated so that, as far as is practicable, they are located on the private property they are intended to protect and not on public land, including an assessment of adequate access points from public roads and along the crest of the proposed works or other means to allow for future repairs; and

iii) all proposed improvement works are consistent with the CZMP for Collaroy-Narrabeen Beach and Fishermans Beach and the Draft Northern Beaches Coastal Protection Policy (2016).

The scope of this review includes a description of the relevant coastal processes, adopted coastal design parameters and sediment budget (**Section 2**), a description of the concept design and alignment of the proposed coastal protection improvement works (**Section 3**) and an assessment of the potential impacts and necessary mitigation measures to not adversely affect the existing processes and beach amenity (**Section 4**). The scope of this review includes consistency checks with the adopted CZMP and Coastal Protection Policy, consideration of the physical impacts and socio-economic impacts of seawalls, evaluation of the expected beach response to the proposed improvement works, an assessment of the expected erosion to the north and potential seawall “end effects”, an assessment of potential impacts of partial or ad-hoc completion of works, a review of the proposed surface and stormwater management measures, horizontal alignment tolerances and estimated cross-shore position impacts on beach amenity, potential mitigation measures, visual amenity and potential impacts on local views.

2. Description of Key Coastal Processes

2.1 Preamble

This review of potential impacts and necessary mitigation measures for the proposed Collaroy-Narrabeen Beach coastal protection improvement works has been undertaken in recognition that sand and other sediment moves on a large scale within coastal sediment compartments. Coastal management activities (including dredging, sand replenishment, beach nourishment and terminal protective works as proposed within the approved CZMP) should take into account coastal processes and other strategic issues on a regional scale. This approach is consistent with the directions of the new NSW Coastal Management Act (2016) where management activities are undertaken within coastal sediment compartments that are defined areas of the coast based on sediment flows and landforms.

Figure 1 shows the boundaries of Sydney's Primary Coastal Sediment Compartment, which extends from Port Hacking, Bundeena in the south to Broken Bay, Box Head in the north, and includes Sydney Northern Beaches and four other Coastal Sediment Compartments as defined in Schedule 1 of the Coastal Management Act (2016). This review is focused on the Collaroy-Narrabeen Beach embayment or sub-compartment, located centrally within the Northern Beaches Coastal Sediment Compartment, which extends from Long Reef Point to Turimetta Head as shown in **Figure 2**.

The description of coastal processes which follows is based on a synthesis of work already completed by others and includes a summary of relevant coastal hazards and design parameters, key physical processes affecting sand movement (beach erosion and recovery) and the sediment budget (sources and sinks) used to formulate a quantitative coastal processes model for the Collaroy-Narrabeen Beach embayment. Long-term climate change and sea level rise impacts are considered also as part of this review.

2.2 Coastal Hazards and Design Parameters

Approximately one third of beach front properties at Collaroy-Narrabeen Beach are at a high or very high risk of damage from coastal erosion, with most properties south of Devitt Street being at risk. The CZMP (2014) presents details of the main coastal hazards for Collaroy-Narrabeen Beach as summarised below, comprising short-term beach erosion (storm demand), long-term beach recession, coastal inundation (wave overtopping) and associated failure of coastal property and infrastructure. Coastal design parameters, comprising elevated ocean water levels, design nearshore water depths (derived from seawall toe scour levels and elevated ocean levels) and wave conditions were determined by the Engineering Consultant as presented in **Appendix B** and summarised below.

The adopted design criteria are based on a minimum 50 years Average Recurrence Interval (ARI) design storm conditions and a minimum 60 years design life. While this has been selected based on a rational risk based approach (as described by Horton and Britton, 2015), it is recommended that detailed design of coastal protection improvement works include consideration of the expected consequences of more extreme events beyond the design event such that the level of damage and consequences are understood and documented as part of the detailed design process. This should be based on demonstrated tolerable damage and expected cost of post storm repairs.

The design criteria and coastal hazards adopted by the Engineering Consultant (**Appendix B**) are reviewed and summarised below.

2.2.1 Design Water Levels

Design ocean water levels have been adopted in the CZMP for Collaroy-Narrabeen based on analysis of long term ocean water level records from Fort Denison as derived by DECCW (2010) comprising a 100 years ARI still water level (excluding wave setup) of 1.44 m above AHD. This level has been confirmed in a more recent study of elevated ocean levels by MHL (2016a) as shown in **Figure 3** with a corresponding 50 years ARI still water level of 1.42 m AHD. MHL (2016a) further found uncertainties in the extreme value analysis methods adopted to be of the order of +0.1 m. The recommended 50 years ARI design still water level offshore of Collaroy-Narrabeen, therefore, is 1.5 m AHD.

Other uncertainties reported by MHL (2016a) based on inter-annual and inter-decadal climate cycle effects on ocean tidal records in NSW of up to +0.25 m are not applicable to the Fort Denison analysis which extends for a sufficient period (over 100 years) and are incorporated within the extreme value analysis results.

Making allowance for wave setup, estimated to be 15% of the design offshore significant wave height (H_{0s}; SPM, 1984), the 50 years ARI design water level at fully exposed shorelines is about 2.7 m AHD (refer to **Section 2.2.3** for design H_{0s}). At less exposed areas (such as the southern end of Collaroy Beach, and Fishermans Beach), equivalent elevated water levels would be reduced due to lower wave setup, namely to about 2.4 m and 2.2 m AHD respectively (CZMP, 2014). Given the empirical nature of the estimation of wave setup, it is recommended that the detailed design of coastal protection improvement works take into account sensitivity analysis of the design water level based on wave setup ranging from 10% to 20% of H_{0s} and/or undertaking site specific modelling. The modelling should also consider that a seawall will truncate the surf zone, and therefore the full quantum of wave setup on a dissipative beach may not be realised when a seawall is present.

2.2.2 Design Toe Scour

A minimum toe level of -1 m AHD has been recommended for structural design by the Engineering Consultant (**Appendix B**). It is agreed that a higher toe level may be considered appropriate given the presence of an erosion-resistant cemented sand layer typically at about -0.5 m AHD, subject to this being supported by site specific geotechnical data and a report prepared by a suitably qualified engineer (see **Appendix B**). This higher level may not be appropriate for design of rigid structures subject to brittle failure and in all cases, given the understood limited finite thickness of this cemented layer, consideration should be given as part of detailed design to the consequences of scour below this to at least -1 m AHD.

2.2.3 Design Wave Conditions

The proposed coastal protection improvement works would reside along the foreshore and the design wave conditions are subject to the depth limited critical breaking wave height determined by the design scour level and water depth a suitable distance (plunge length) seaward of the structure (SPM, 1984). The design deepwater offshore wave conditions are also relevant in terms of the design wave setup as discussed in **Section 2.2.1**. As described in the CZMP (2014), beach erosion and relatively large wave run-up is strongly linked to the occurrence of high wave conditions with elevated ocean water levels, so erosion and run-up are more likely to be significant when large waves coincide with a high tide. A 6 hours duration is agreed to be appropriate for design, as storms with a duration of 6 hours are likely (50% probability) to coincide with high tide on the NSW coast (which is a prerequisite for elevated water levels to occur). A 1 hour duration only has an 8% probability of coinciding with high tide. Notwithstanding this, the consequences of 1 hour duration design wave conditions should be evaluated as part of the detailed design and may be particularly important for checking the stability and expected damage of the proposed coastal protection improvement works.

Extreme value offshore wave conditions have been recently re-evaluated for Sydney by Couriel et. al (2016) from offshore Waverider records as shown in **Figure 4** for both 1 hour and 6 hours duration events. The indicated 6 hours duration, 50 years ARI offshore significant wave for Sydney is 8.2 m (with a peak spectral wave period, T_p of 12 s).

Based on modelling completed by WorleyParsons (2009), peak 100 year ARI wave heights reduce to about 75% of fully exposed values south of Fielding Street at Collaroy Beach with the fully exposed values applying north of Stuart Street at Collaroy-Narrabeen Beach. More recent calibrated nearshore wave transformation modelling undertaken by Baird Australia and MHL (2015) for the entire NSW coast is now available through the NSW Nearshore Wave Transformation Tool and should be utilised as part of the detailed design process.

2.2.4 Coastal Inundation (Wave Overtopping)

As described in the CZMP (2014), areas along Collaroy-Narrabeen Beach at particular risk from coastal inundation from wave overtopping during elevated ocean levels and large waves are south of Devitt Street at Collaroy-Narrabeen Beach, and in particular south of Stuart Street, with the area surrounding Collaroy SLSC and Collaroy Services Beach Club being particularly vulnerable to coastal inundation as this area is generally below 4 m AHD.

Detailed design of the proposed coastal protection improvements works will need to account for storm wave overtopping rates as well as local rainfall runoff drainage (see **Section 4.7**). Expected average storm wave overtopping rates have been estimated for four typical cross sections along the study area as presented in **Appendix A** (**Section A6.4**). The preliminary analytical analysis presented is based on the adopted design conditions and indicates that a minimum design crest level of 6.5 m AHD should be adopted for a conventional rock rubble mound armour design to satisfy EurOtop (2007) recommended average wave overtopping limits (see **Table A3**), including consideration for future sea level rise and allowing for some albeit minor damage to foreshore areas, dwellings and infrastructure.

It is noted that it is difficult to make accurate estimates of wave overtopping rates through analytical calculations alone. Small shifts in beach slopes, design water levels and rock profiles can cause large variability in results. This advocates a reasonable factor of safety in design be adopted given natural variability also in design conditions within the surf zone. Other pertinent factors that should be considered in detailed design include the fact that a single wave under storm conditions can result in wave overtopping rates that are up to 100 times greater than the estimated average wave overtopping rates (van der Meer 1994) with increased overtopping volumes and high flow velocities. These and other factors may contribute to hazard ratings for people and properties above and behind the proposed coastal protection improvement works.

The minimum recommended crest height of 6.5 m AHD for a conventional rock rubble mound armour revetment would nevertheless be subject to site-specific factors, including the capability of the local drainage system, nature of buildings (value and construction materials) and proximity of these and other assets landward of the proposed revetment. For non-conventional composite revetment designs or designs that incorporate vertical or near vertical seawalls, higher wave overtopping rates are expected, with resulting higher minimum necessary design crest levels. Structures incorporating explicit design allowances and triggers for future sea level rise adaptation, conversely may be able to adopt lower initial crest levels. For all non-conventional rock rubble mound armour structures or other innovative design situations, it is recommended that physical model testing be undertaken to verify wave overtopping rates, overall stability and the suitability of any proposed works as part of the detail design and development approval process.

2.2.5 Storm Demand

As described in the CZMP (2014), the study area has been subject to damaging coastal storms in the past and most recently in June 2016. The area is expected to continue to be exposed to such storms at irregular and unpredictable intervals in the future. These storms are most likely to occur in Autumn and Winter, and are least likely to occur in Summer, although major coastal storms in NSW can occur at any time (Shand et al, 2011). The most damaging storms in the study area have occurred as a series of closely linked storms, rather than being from a single particularly severe storm. In this way the beach may already be in a depleted state and hence more exposed to damage at the time of subsequent storms. A key factor in the erosiveness of a storm, besides the storm energy, is also the water level occurring during the storm contributing to the critical maximum breaking/broken waves able to reach the foreshore as described in **Sections 2.2.1** to **2.2.3** inclusively.

The design beach erosion volumes (above 0 m AHD; often termed Storm Cut or Storm Demand) as reported in the CZMP (2014) were estimated from historical observations for Collaroy-Narrabeen Beach and are as follows:

- 250 m^3/m north of Frazer Street;
- linearly reducing to 200 m^3/m at Collaroy Services Beach Club; and
- linearly reducing further to 150 m^3/m south of Collaroy SLSC.

As most of the existing seawalls have not been engineered, in defining acceptable risk development setback lines (**Section 2.2.7**), the CZMP (2014) assumed that the storm demand was reduced by 20% where such structures are present (CZMP, 2014).

2.2.6 Underlying Beach Recession

Unlike storm related beach erosion outlined above, where sand eroded from the beach is temporarily deposited in offshore bars and returns to the beach under milder wave conditions, beaches may also experience persistent long-term erosion (termed recession), where sand is permanently lost from the active beach system (by natural or anthropogenic influences) or is permanently relocated to an adjusted profile from climate change related evolution in wave climate or sea level changes.

Collaroy-Narrabeen Beach is not subject to any significant beach recession as described in **Section 2.3** with long-term shoreline changes as estimated in the CZMP (2014) as follows:

- Long-term beach recession due to net sediment losses (see **Section 2.2.6**) of about 0.05 m/year along Collaroy-Narrabeen Beach; and
- Long term beach recession due to historical sea level rise of about 0.04 m/year along Collaroy-Narrabeen Beach based on the Bruun Rule and a beach slope of 1:30.

2.2.7 Adopted Development Setbacks and Controls

The CZMP (2014) presents a detailed risk assessment (based on AGS, 2007) to define appropriate development setbacks and controls along Collaroy-Narrabeen Beach as reproduced in **Figure 5**. The resulting minimum setback acceptable risk lines for new development on conventional foundations and for new development on piled foundations include consideration of protection offered by existing coastal structures (albeit limited to an assumed 20% reduction in beach erosion Storm Demand) south of Devitt Street (**Figure 5c** and **Figure 5d**). This work clearly demonstrates the immediate risk present for existing development in the study area where the coastal protection improvement works are proposed from the north-east corner of the Collaroy Services Beach Club to Devitt Street.

2.3 Physical Coastal processes

2.3.1 Preamble

With the heightened attention on beach erosion, people may not be cognisant that beaches are primarily accretionary features formed by wave action transporting sediments towards and along the shore. The key physical processes responsible for beach erosion were described in **Section 2.2** together with other coastal hazards. In this Section, all of the main physical erosive and accretionary processes responsible for sediment movement into, within and out of the Collaroy-Narrabeen Beach embayment are outlined and quantified as far as practicable within available information.

To best understand the present day coastal processes operating along Collaroy-Narrabeen Beach, it is important to understand the geological history of the NSW coastline, the broader regional scale sediment dynamics and the key physical processes responsible for the present form of the Sydney Northern Beaches Coastal Sediment Compartment and the Collaroy-Narrabeen Beach Sub-Compartment (**Figure 2**).

As described in the CZMP (2014), mean global sea level was around 140 m below its present level about 17,000 years ago when the Sydney Northern Beaches coastline was located about 20 km offshore from its present position. As warmer conditions prevailed following the last glaciation and the earth’s tilt approached the sun (see Milankovitch earth wobble as described by Hays et. al., 1976), sea level gradually rose to near its present level about 6,000 years ago, since which time it has remained relatively stable (±2 m; this period being referred to as the Holocene "still stand"). During the post glacial rise in sea level, onshore (transgressive) transport of sediment from large sand bodies offshore occurred between the bedrock controlled valleys of the Cumberland Plain to form Sydney’s present pocket beaches. This onshore transgression slowed over the more recent stable Holocene epoch as Sydney’s beaches aligned to the dominant incident wave energy from the SSE direction. Narrabeen Lagoon was formed as the beach system developed during the post glacial transgression to form the existing foredune barrier and cut off existing creek valleys and the low lying area which now interacts with the ocean through the lagoon entrance at North Narrabeen (PWD, 1985).

Sydney’s beaches are characterised by a series of prominent Hawkesbury sandstone and Narrabeen Group outcropping headlands which largely contain sediments within these major features. Only following rare and sporadic major or extreme coastal storms, able to transport sediments sufficiently offshore, do littoral sediments bypass these headlands to neighbouring compartments and move ashore there via onshore transport under calmer shore oblique waves. Coastal sediment compartments characterised by sufficient offshore inner-shelf sand bodies (as may be the case for some of Sydney’s coastal sediment compartments) or other littoral sand supplies, can slowly replenish some of these long-term sporadic sediment losses. As such, the sandy beaches along Sydney’s Northern Beaches can be viewed as generally stable features of these long term accretionary processes. The present coastal hazards dilemma at Collaroy-Narrabeen Beach is well accepted to be primarily a consequence of development having been located within the presently active littoral zone.

Sydney’s Primary Coastal Sediment Compartment (as defined in Schedule 1 of the Coastal Management Act, 2016) extends from Port Hacking to Broken Bay as shown in **Figure 1**, and includes Sydney Northern Beaches Coastal Sediment Compartment that extends from North Head to Barrenjoey Head. The Collaroy-Narrabeen Beach embayment or sub-compartment is located centrally within the Northern Beaches Compartment and extends from Long Reef Point to Turimetta Head as shown in **Figure 2**.

The main physical erosive and accretionary coastal processes relevant to Collaroy-Narrabeen Beach are summarised using a Quantitative Coastal Processes Model as illustrated in **Figure 6** which comprises:

- ⇨ Inner Continental Shelf interaction;
- ⇨ Longshore sediment transport;
- ⇨ Lagoon entrance dynamics;
- ⇨ Cross-shore sediment transport;
- ⇨ Headland bypassing;
- ⇨ Fluvial sediment inputs and fluvial deposition
- ⇨ Aeolian transport
- ⇨ Anthropogenic influences; and
- ⇨ Sand grain size abrasion and headland weathering.

Each of these processes is described and quantified below. It is noted that Fishermans Beach and Turimetta Beach, which form part of the Collaroy-Narrabeen Coastal Sediment Sub-Compartment (**Figure 2**) have been omitted from **Figure 6** only for simplicity, as the primary interconnections are low and infrequent (north and southbound) between Fishermans Beach and Collaroy Beach and between Turimetta Beach and North Narrabeen as described in **Section 2.3.6** under headland bypassing and as noted on **Figure 6**.

2.3.2 Inner continental shelf interaction

The Inner Continental Shelf near Sydney is interspersed with marine sand deposits in depths ranging from around 20 m to 75 m as described by AECOM (2010) in their Beach Sand Nourishment Scoping Study for Sydney Coastal Councils Group. In most places the 'Sydney Inner Shelf Sand Body' (as described by Roy, 2001) displays gently seaward sloping profiles, which are the seaward extensions of inshore and surf zone beach slopes. At several locations, however, directly adjacent to cliffs, such as Cape Banks (**Figure 1**), the deposits form mildly to strongly convex bodies up to 50 m thick in 20 m to 40 m water depth. These sand bodies are geological features that were formed during the post-glacial marine transgression and subsequent still stand (as described in **Section 2.3.1**). As the sea level rose, the unconsolidated beach sediments were pushed ashore progressively under wave action and as the sea level continued to rise, cliffs hindered this westward re-distribution of the sand, which then accumulated against the cliff face only to be submerged as the present day sea level was attained.

At present, the rates of sand transport of Sydney's inner-shelf sands are assessed to be very low (AECOM, 2010), with further onshore migration at rates estimated to be less than 0.5 m^3/m/year (equivalent to less than 2,000 m^3/year along the entire Collaroy-Narrabeen Beach embayment; **Figure 6**) with indiscernible shoreline effects taking place over hundreds or thousands of years. It is noted, however, that where extensive inner-shelf sand bodies exist, such as for the Forster/Tuncurry coastal sediment compartment, Roy (1997) argues that up to 200,000 m^3/year of sediment is transported onshore, which is about equal to the longshore sediment transport rate there.

The nearshore sand body at Cape Banks has compatible sediment properties to Collaroy-Narrabeen Beach with an estimated sand volume of approximately 10M m^3 (based on a sand body depth of 5 m) although reserves may be considerably greater (AECOM (2010). Of particularly relevance to the Collaroy-Narrabeen Beach sediment budget on a geological time-scale, this volume of sediment would be sufficient to cater for the estimated 9M m^3 of sand required to maintain the present recreational amenity of all of Sydney's ocean beaches with natural ongoing transgression in response to the estimated long-term recessional effects of sea level rise described in **Section 2.2.6** (volumes taken from AECOM, 2010).

2.3.3 Longshore littoral sediment transport

Longshore sediment transport ("littoral drift") occurs primarily by waves breaking at an angle to the shore, moving sediments along the shoreline (feeder currents to rips and longshore variations in water level resulting from nearshore wave conditions and wind stress may also cause longshore littoral transport; NSW Government, 1990). Because waves and other wind conditions arrive at beaches from different directions, longshore sediment transport can occur in different directions at different times. For Collaroy-Narrabeen Beach, wave directions north of east generally favour southerly longshore sediment transport with northerly transport more likely when waves come from the south of east (the predominant wave direction; Kulmar et.al., 2005). Southward littoral drift leads to sand accretion at Collaroy Point (towards The Kick; **Figure 6**) and counter-clockwise rotation of the beach, with progressive widening of Collaroy Beach and narrowing of North Narrabeen Beach. Under typically predominant northerly littoral drift, Collaroy Beach narrows as North Narrabeen Beach widens, with sand also entering the Lagoon entrance (**Section 2.3.9**).

Harley et.al. (2011) undertook a comprehensive analysis of embayment rotation at Collaroy-Narrabeen Beach using more than 30 years of beach profile data and confirmed that north easterly waves cause counter-clockwise shoreline rotation, with such behaviour particularly evident in summer/autumn and the converse situation occurs for southerly waves being more typical in winter/spring. The primary cause of beach rotation for the Collaroy-Narrabeen embayment, however, was indicated to be associated with alongshore variability in cross-shore sediment processes (see **Section 2.3.5**) attributable to greater exposure to more typical storm waves from the south at the northern end of the beach compared with the southern end. This relatively larger cross-shore movement of the shoreline at North Narrabeen compared with Collaroy Beach due to higher storm demand and recovery volumes was indicated by Harley et.al. (2011) to account for 60% of the overall shoreline variability. The two modes of shoreline variability described also appeared to be linked to the El Niño/Southern Oscillation (ENSO), with El Niño/La Niña periods coinciding with an overall seaward/landward and clockwise/counter-clockwise rotation of the shoreline.

Although not reported by Harley et.al. (2011), personal communication from Dr Harley advised that the gross rates of northward and southward littoral drift sand transport for Collaroy-Narrabeen Beach as shown in **Figure 6** were:

- -50,000 m^3/year northward, predominantly from April to October, of which approximately 10,000 m^3/year accretes in the lagoon mouth;
- +50,000 m^3/year southward, predominantly from October to April, of which approximately 10,000 m^3/year is mechanically removed from the lagoon mouth and transported by truck to the southern end of the beach.

These estimated net longshore transport rates are consistent with marine sand infill rates at Narrabeen Lagoon entrance as reported by MHL (2009) and Morris and Turner (2010).

2.3.4 Lagoon entrance dynamics

Narrabeen Lagoon is classified as an Intermittently Closed and Open Lake or Lagoon (ICOLL). The lagoon is usually open to the sea (at North Narrabeen) and experiences tidal influence, although following prolonged dry periods and wave conditions that are conducive to northerly littoral drift (**Section 2.3.3**), the entrance can become closed to the sea until naturally breached by lagoon catchment runoff flows and/or mechanical intervention (according to Council's entrance management plan; **Section 2.3.9**).

Because the energy of the incoming (flood) tide exceeds that of the outgoing (ebb) tide (due to energy losses through the entrance and bars), and the additional agitation of sand by waves breaking at/near the entrance, the amount of sand transported into the entrance on each flood tide exceeds that which is transported seaward on the ebb tide. This leads to a gradual and progressive accumulation of sand within the entrance shoals known as the flood tide delta. Once this delta area becomes saturated with marine sands, the Lagoon's entrance will typically close without natural or human intervention. The delta sand is naturally returned to the active beach zone during high catchment rainfall/runoff events, but where necessary, Northern Beaches Council mechanically removes the sand to replenish the beach (a Policy consistent with working with nature).

The rate of infill of the flood tide delta varies with environmental conditions. Based on the volumes and frequency of mechanical interventions that have taken place over the past 25 years (**Section 2.3.9**), and the estimated net longshore transport rates to the north (**Section 2.3.3**) the adopted sand infill rates for Narrabeen Lagoon entrance range from 10,000 – 25,000 m^3/year. Typical dredging campaigns have removed 30,000 – 60,000 m^3 every 3 to 5 years. The volumes of sand returned to the beach from the entrance following a lagoon breakout or catchment runoff event depends on the lagoon water level, entrance shoal level and extent, and the ocean tidal stage. MHL (1989) reported typical lagoon breakout sand volumes of the order of 3,000 to 8,000 m^3. Typical catchment runoff events return 2,000 to 30,000 m^3 of marine sand from the delta to the offshore bar and beach system; the latter volume being associated with major catchment events of greater than about 20 years ARI.

2.3.5 Cross-shore sediment transport (storm cut and beach recovery)

Beaches erode during coastal storms as elevated ocean water levels and increased wave heights lead to increased energy at the shore. Strong shoreward surface currents establish across the surfzone as broken waves transport large quantities of white-water shoreward, further elevating nearshore water levels (wave setup). Mega-rips and strong undertow currents develop to return flows seaward, transporting large quantities of eroded beach sand to form increasingly seaward offshore bars. Provided sufficient sand reserves exist within the beach and sand dune system, a new dynamic equilibrium beach profile is reached for the atypical storm conditions as the surfzone widens and the energy arriving at the shore is sufficiently diminished. The total volume of sand eroded from the beach (storm cut or storm demand; **Section 2.2.5**) typically occurs over a matter of hours or days.

As waves and ocean levels return to normal after the storm, rips and undertow currents abate and the characteristic orbital water motions under waves that have an asymmetric net shoreward component (in the direction of travel of the waves), gradually transport the eroded sand back onto the beach. This process occurs typically over months or years and is referred to as beach recovery. Full beach recovery after a major or extreme storm can take decades, and can also result in sand being transported onshore into a neighbouring beach (headland bypassing; **Section 2.3.6)**, and relies also on onshore winds to return sand to the upper beach and dune system (see aeolian sand transport described in **Section 2.3.8**).

Based on the relevant length of beach affected and the storm cut volumes (above AHD) adopted in the CZMP (2014; **Section 2.2.5**), the total volumes of sand exchanged offshore and onshore during and after major storms (as shown in **Figure 6**) would be up to about:

- ± 725,000 m^3 north of Frazer Street;
- ± 84,000 m^3 between Frazer Street and the Collaroy Services Beach club; and
- ± 31,500 m^3 between Collaroy Services Beach club and Collaroy SLSC.

It is noted that during a particular coastal storm, different parts of the beach will erode to different degrees depending on their relative exposure to the incident wave direction. Areas adjacent to rip heads (or mega rips during major and extreme storms) are also expected to have higher storm cut volumes than adjacent non-rip affected areas. The design storm cut volumes presented in **Section 2.2.5** are representative of upper limit values that would be expected at rip heads and/or the more exposed parts of the beach during a particular storm event. While the total sum of the volumes of sand that may be exchanged offshore and onshore during and after major storms estimated above for the three areas of Collaroy-Narrabeen Beach are unlikely to occur simultaneously during a single event, their total sum could be approached through a series of successive major events of different incident wave directs. As such, these volumes could be considered to represent an upper bound limit of cross-shore sand transport for Collaroy-Narrabeen Beach.

During the June 2016 East Coast Low storm in NSW, Harley (2016) reported that Collaroy-Narrabeen Beach experienced a total cross-shore storm erosion volume of about 400,000 m^3 with a maximum storm cut of 228 m^3/m at North Narrabeen and 158 m^3/m along the study area south of Devitt Street as shown in **Figure 7**. It is noteworthy that the June 2016 event was characterised by a total erosion volume of less than half of the upper bound limit of storm demand that could occur for a series of successive multi-directional storms.

Beach recovery does not invoke the sense of crisis that major beach erosion does, so studies of beach recovery rates are less common than those for beach erosion. Notwithstanding this, four studies of beach recovery along Australia's eastern seaboard have been utilised to quantify expected beach recovery rates for the study area as described in **Appendix A** (**Section A7.2**), including a recent study specifically for Collaroy-Narrabeen Beach by Phillips et. al. (2015). Low, average and rapid beach recovery rates of 0.07 m/day, 0.14 m/day and 0.50 m/day (equivalent to approximately 0.2 m^3/m/day up to 1.5 m^3/m/day) are considered applicable to Collaroy Narrabeen Beach as shown in **Figure 6**. A possible beach recovery period of between 3 months and more than 2 years would be expected using these rates to recover from the June 2016 storm erosion.

The adopted beach recovery rates have been used also to estimate the time it would take for sand levels to increase from an eroded beach state at the back of the beach along the line of the existing ad-hoc coastal protection works. Expected back beach recovery rates range from about 90 days to more than 640 days for the beach to recover from an eroded level of 0.0 m AHD to +3.0 m AHD as detailed in **Appendix A** (**Table A7** to **Table A9** inclusively).

2.3.6 Headland bypassing

As described in the CZMP (2014), the beaches in the study area are generally surrounded by headlands that limit the transfer of sediment between embayments. The coastal sediment compartment of Collaroy-Narrabeen Beach, includes Fishermans Beach and Turimetta Beach and is bounded by Long Reef Point and Turimetta Head as shown in **Figure 2**. Due to the broad and extensive seaward extent of Long Reef Point, the only sand expected to enter the Collaroy-Narrabeen compartment from the south would be via inner-shelf/offshore sand bodies (**Section 2.3.2**; **Figure 6**). That is, the Collaroy-Narrabeen Beach compartment can be considered generally to be a closed compartment with regard to longshore sediment transport, in that it does not supply significant volumes of sediment to adjacent embayments nor gets supplied with significant volumes of sediment from adjacent embayments (PWD, 1985; CZMP, 2014). The hypothesis of relatively closed compartment is supported also by negligible change in beach volume over time since records and observations began (see sediment budget discussion in **Section 2.3.11**).

The Collaroy-Narrabeen Beach embayment itself, however, is inter-connected between the smaller headlands as evidenced by sand moving both north and south from and into the adjoining Fishermans Beach in the south and Turimetta Beach north of Narrabeen Head. PWD (1987) indicated that approximately 2,000 m^3/year on average is transported north of Narrabeen Head (and potentially bypassing Turimetta Head), although it is expected that up to 10,000 m^3 of sand could be transported north of Narrabeen Head following a major entrance breakout and southerly beach recovery swell conditions. Most of the sand entering Turimetta Beach is expected to be returned to Narrabeen Beach via the extensive North Narrabeen offshore bar system during east and north-easterly wave events.

2.3.7 Fluvial sediment inputs and fluvial deposition

While no specific studies have been undertaken to characterise the specific properties of sediments carried by stormwater runoff that drains onto Collaroy-Narrabeen Beach and Narrabeen Lagoon, it is understood from Council’s stormwater maintenance experience that there is no evidence of sand sized sediments being discharged from any of the existing stormwater pipes that drain onto the beach.

Specific studies into sedimentation of Narrabeen Lagoon (NSW Public Works Department, 1984) have indicated that fluvial sediment loading is deposited within the lagoon to form creek entrance levees and deltas with most fluvial sediments comprising fine clays and silts deposited within the wider lagoon which is progressively becoming shallower. Where fluvial sediments are re-suspended during major catchment runoff events, these fine sediments do not contribute to the active sand volume on the beach as they remain in suspension until they are transported further offshore. There is no evidence that Narrabeen Lagoon or the existing stormwater drains provide any significant net contribution of sand sized material to the beach and hence are shown as zeros in **Figure 6** for simplicity. The only interaction between the Lagoon and beach sediments is associated with the flood tide delta (a temporary sediment sink) as described in **Section 2.3.4**.

2.3.8 Aeolian sediment transport

Aeolian sand transport (wind-blown sand) occurs when mostly dry sand is carried by wind. Onshore winds are responsible for natural dune formation, where vegetation cover helps trap aeolian sand and encourage dune formation. The dunes themselves become a temporary sediment sink (removed from the active beach system) until a major coastal storm erodes this material back into the active beach (see **Section 2.3.5**).

As described in the CZMP (2014), aeolian sediment transport issues were more significant prior to the NSW Government's Beach Improvement Program (in the 1970's and 1980's) due to the lack of dune vegetation coverage in those earlier times, particularly at areas such as north of Devitt Street. Aeolian sand transport issues still remain at some locations like Mactier Street, Clarke Street and Stuart Street, although no significant net loss of sand from the beach occurs by aeolian processes (**Figure 6**) as Council periodically sweeps this material back onto the beach.

The importance of sand stabilisation provided by dune vegetation to stabilise dune systems and protect them from wind erosion, even for the limited incipient dune systems south of Devitt Street is emphasised.

2.3.9 Anthropogenic influences

Three main human interventions that affect the sediment budget (sources and sinks) of Collaroy-Narrabeen Beach are:

i) the mechanical removal of Lagoon entrance sands and their return to the beach (referred to as "beach sand recycling" after CZMP, 2014);

ii) the placement of extra sand on the beach from building site excavations (sand nourishment); and

iii) the incidental loss of sand from general human activities.

As described in **Section 2.3.4**, the entrance to Narrabeen Lagoon is periodically filled with marine sand from the beach and during extended dry periods, can become closed to the ocean. Adverse impacts on water quality, decreased biodiversity and increased severity of flooding of low lying areas surrounding the lagoon result when the lagoon entrance remains closed for extended periods.

To manage this dynamic system and reduce the risk of flooding, Northern Beaches Council, with the assistance of the NSW Government under its Floodplain Management Program, undertake sand clearance operations every three to five years (on average). This work is part of the management actions in the adopted Floodplain Risk Management and Estuary Management Plans for Narrabeen Lagoon and the adopted CZMP (2014).

Sand mechanically removed from the lagoon's entrance is transported by trucks to Collaroy Beach and South Narrabeen Beach; from where it originated (recycled). This management activity has taken place since at least 1975, with more recent sand recycled quantities as summarised in Cameron (2010) and the CZMP (2014) of 390,500 m^3 between 1982 and 2006 (equivalent to about 16,000 m^3/y) and 163,500 m^3 between 1999 and 2011 (equivalent to about 23,000 m^3/y) as summarised in **Figure 6**. The total volume of sand recycled during each dredging entrance campaign has ranged from about 20,000 m^3 to 70,000 m^3, with the most recent campaign in October 2016 proposing to recycle about 50,000 m^3 to assist with beach recovery following the June 2016 storm erosion.

Extra sand (not originating from the contemporary beach compartment) has been obtained from coastal building site excavations and used to nourish Collaroy-Narrabeen Beach comprising +22,000 m^3 between 2001 and 2010 (Cameron, 2010) or +30,500 m^3 up to 2014 (CZMP, 2014) as indicated in **Figure 6**.

In addition to the direct mechanical recycling and extra nourishment of sand, human activities generally can also result in accidental removal of beach sand, attached to people, towels and surf craft. This anthropogenic sediment sink has not been reported previously for Collaroy-Narrabeen Beach and is estimated from relevant albeit limited available literature (see **Appendix A, Section A8**) to be -150 m^3 to -400 m^3 each year. While compared with other anthropogenic influences, this does not appear to be a large amount of sand, this loss of sand would result in up to 6 mm/year beach recession, or about 12% of the underlying beach recession or 15% of the historic sea level rise recession estimated in the CZMP (2014).

2.3.10 Sand grain size abrasion and headland weathering

Sand losses from sediment abrasion (winnowing) and sand accumulation from headland and rock platform weathering have not been previously documented for Collaroy-Narrabeen Beach and are discussed here for completeness.

Wynne et al (1984) reported the following from Komar (1976). Studies reported in Komar (1976) showed that particles smaller than about 0.25 mm (most NSW beaches) do not experience significant abrasion, which is believed to be due to the particles having low inertia in collision. Most NSW beaches have a shell content of less than 15%, but there are some beaches, including Collaroy-Narrabeen with much higher shell contents. Analysis presented in PBP (1993) indicated shell content in six samples taken from water depths shallower than 20 m ranged from 20% to 35%, with higher values (50% to 65%) in deeper water close to reefs. While knowledge of shell production rates and degradation is not well known, other studies such as Mariani et al (2013) assumed that a long term balance has been reached between shell production and degradation.

While the soft calcium carbonate shell fragment is abraded more rapidly than silica sand, even this is surprisingly resistant once it is in small sand size fragments (Komar, 1976). As such, sand abrasion losses have been omitted from the quantitative coastal processes model shown in **Figure 6**.

As described by DLWC (2001), weathering and erosion of headlands and rock platforms delivers small volumes of rock fragments to the beach but overall this is a minor component of NSW beach sand and hence also omitted from **Figure 6**. Chapman et al (1982) assumed a rate of +5 mm/year and noted that its contribution to sediment budget was very small except where the proportion of cliffs to beaches is large (which is not the case at Collaroy-Narrabeen Beach). It is also noted that Collaroy-Narrabeen Beach (as for most of NSW beaches) does not receive any significant quantities of sand-sized sediment from the Lagoon or stormwater drainage systems (**Section 2.3.7**). The dominant component is well-rounded, often iron-stained quartz sand that has survived many thousands of years of reworking by wave action since the last glacial period combined with shells of uncertain age (refer to **Section 2.3.2**).

2.3.11 Quantitative Coastal Processes Model and Sediment Budget

The main coastal processes for Collaroy-Narrabeen Beach as described above and illustrated in **Figure 6** are summarised as follows using the following sediment budget related colour coding:

- ⇨ Sediment budget process sources (additions) are depicted as **+bold green**;
- ⇨ Sediment budget process sinks (losses) are depicted as -underlined red; and
- ⇨ Balanced or neutral sediment budget processes are depicted as *italic grey*.

- Inner Continental Shelf interaction (**< approx. +2,000 m^3/y**);
- Net longshore sediment transport (-10,000 to -30,000 m^3/y; mostly into lagoon);
- Lagoon entrance dynamics (see *longshore transport and entrance management*);
- Cross-shore sediment transport (< *approx. ±840,000 m^3*);
- Headland bypassing (**+0 m^3/y @Long Reef Point**, *±2,000 to ±10,000 m^3/y @Narrabeen Head* and <approx. -2,000 m^3/y @Turimetta Head);
- Fluvial sediment inputs and deposition (*approx. ±0 m^3/y*);
- Aeolian transport (*approx. ±0 m^3/y*);
- Entrance management (**+15,000 to +25,000 m^3/y** anthropogenic sand recycling);
- Building sites (**+2,000 to +3,000 m^3/y** anthropogenic sand nourishment);
- Incidental Removal (-150 to -400 m^3/y anthropogenic); and
- Sand grain size abrasion and headland weathering (*approx. ±0 m^3/y*)

The above sediment budget indicates that onshore transport of inner-shelf sand, although small in the scale of other cross-shore and longshore processes, has the potential to balance the expected long-term sand losses attributable to post storm headland bypassing and potentially also to assist natural beach transgression in response to sea level rise (**Section 2.2.6**).

The careful management of the lagoon's entrance (by recycling sand) and the extra sand nourishment undertaken from building sites have helped maintain and even prograde the finely balanced sediment budget of Collaroy-Narrabeen Beach. This is supported by historical aerial photogrammetry showing beach accretion of 0.1 m/year from 1951 to 2006 and more recent beach survey data from 1976 to 2008 showing a volumetric accretion of +0.5 m^3/m/year (CZMP, 2014). Notwithstanding this, the CZMP (2014) makes allowance for long-term beach recession due to net sediment losses of about 0.05 m/year and due to historical sea level rise of about 0.04 m/year along Collaroy-Narrabeen Beach (**Section 2.2.6**).

Because the Collaroy-Narrabeen Beach embayment is essentially a stable closed system, the most significant processes in terms of beach fluctuations and shoreline alignment are cross-shore and longshore sediment transport, including the alongshore variability in onshore and offshore movements (**Section 2.3.3**) and the time expected for beach recovery following major storms. This quantitative review of the Collaroy-Narrabeen Beach coastal processes validates the contemporary understanding that the main cause of the existing coastal hazards is that development has taken place within the active coastal zone. The likely impacts of the proposed coastal protection improvement works (as described in **Section 3** below) on the coastal processes and beach amenity are discussed in **Section 4**.

3. Description of Proposed Coastal Protection Works

3.1 Preamble

Approximately one third of beach front properties at Collaroy-Narrabeen Beach are at a high or very high risk of damage from coastal erosion. These properties reside between Devitt Street, Narrabeen and the Collaroy Beach Services Club in Collaroy. Properties affected by coastal hazards as defined in the CZMP (2014) and NBC (2016) include 377 beachfront addresses comprising mostly private residential dwellings, high rise apartments, the Collaroy Beach Services Club, the South Narrabeen SLSC, public carparks and public recreational areas.

Based on NSW legislation, beachfront landowners can submit a Development Application for construction of a new seawall or upgrading of the existing ad-hoc coastal protection works. Beachfront property owners who choose to construct new or upgraded seawalls will directly benefit from these works. As a result, the now certified CZMP (2014) recommends that private property owners fully fund these works.

The implementation of consistent and appropriate protective works on Collaroy-Narrabeen Beach is complex and will require co-ordination of the various property owners, consideration of funding and maintenance mechanisms, and detailed design guidance. In recognition of this, one of the highest priority actions in the CZMP (2014) is to develop guidelines for the protective works to resolve these issues. The guidelines include design standards, alignments and required setbacks. Additionally, the guidelines and Northern Beaches Council's (2016) Draft Coastal Erosion Policy recommend that as far as practicable all future coastal protection improvement works be contained on private property and existing protective works on public land be removed where appropriate.

Application of the guidelines will ensure that any future protective works are constructed to the prescribed standards ensuring consistency in siting and quality as well as maintenance of the beach environment.

Northern Beaches Councils has engaged an Engineering Consultant to prepare a concept design and conceptual alignment for protection works with a Minimum Average Recurrence Interval (ARI) design event of 50 years and a minimum structural design life of 60 years along the study area from the northeast corner of Collaroy Beach Services Club up to Devitt Street with the following aims:

1. Ensures the long-term coastal processes of the Collaroy-Narrabeen Beach embayment are maintained (relative to the existing situation which includes a variety of non-engineered, ad-hoc works);
2. Ensures that the presence of the works will not adversely impact on adjoining private and public properties, or affect the long-term amenity of the adjoining beach and surf zone (compared with the status quo);

3. Are contiguous, similar and integrated with adjoining protective works constructed in the embayment;
4. Are a consistent design standard that provides an appropriate level of protection from coastal erosion for affected properties;
5. Is situated so that, as far as is practicable, it is located on the private property it is intended to protect and not on public land;
6. Any excavation to construct protection works will not undermine the foundations of existing built structures;
7. Unobstructed access is available behind the crest of the protection works during construction;
8. Access points are incorporated for future unobstructed maintenance;
9. Includes provision for public access (e.g. as part of the structure, or by siting the structure) when the works are exposed following erosion events (consideration should be given to incorporating some provision for access along the beach at a lower level in the event that the protection works are exposed); and
10. Is consistent with relevant legislation, guidelines and policies.

The following Sections describe the proposed coastal protection improvement works for the study area between the Collaroy Beach Services Club and Devitt Street, comprising the proposed alignment and representative preliminary concept design cross-sections for areas traversing public areas at:

i) the car park north of the Collaroy Beach Services Club;

ii) the Fraser Street Reserve; and

iii) the South Narrabeen SLSC.

The adopted design criteria for the proposed coastal protection improvement works are described in **Section 2.2** and **Appendix B**. An assessment of the proposed coastal protection improvement works is presented in **Section 4**.

3.2 Alignment

Consistent with the objectives of the CZMP (2014) and Council's Draft Coastal Erosion Policy (2016), the proposed seawall alignment is located as far landward as possible in consideration of access requirements along the crest, and within the private property it is intended to protect as far as practicable. Detailed consideration of site specific aspects of the existing situation for each affected property was given by the Engineering Consultant in determining the proposed alignment, including retreat of existing ad-hoc works where practicable (such as the proposed regression of works at Wetherill Street) in order to maximise beach amenity as detailed in **Appendix C** and illustrated in **Appendix D**.

The resulting recommended coastal protection improvement works alignment is presented in **Appendix D**, which includes plans showing the typical extent of existing rocks seaward of property boundaries as of 8th June 2016, the maximum landward position of existing rock protection, and where retention of existing works is likely to be appropriate[1] or where improvement works or new coastal protection works will be required. **Appendix D** illustrates also where the proposed coastal protection improvement works alignment is controlled by the crest or by the toe.

3.3 Representative Concept Design Cross-Sections

Representative concept design cross-sections have been prepared by the Engineering Consultant for the proposed coastal protection improvement works along public land areas comprising the Collaroy car park, Fraser Street Reserve and the South Narrabeen SLSC as presented in **Appendix D**. These comprise rock rubble mound armoured seawalls with a minimum of two layers of primary rock armour with a median nominal mass of 3.8 tonnes (for igneous rock) or 5.0 tonnes (for sandstone). The proposed concept design seawall crest elevations range from 4.5 m above AHD to 6.0 m AHD as shown in **Appendix D**. The concept design toe level is nominally at -1 m AHD, or down to the level of the cemented sand layer, which is generally present along the study area at around -0.5 m AHD. This design toe level takes into account the inherent flexibility of the proposed rock rubble mound protection works that are able to tolerate some settlement should the beach erode below -1 m AHD during an extreme storm beyond the design conditions. Alternative seawall designs to rock may require deeper foundations design as determined by a suitably qualified engineer (**Appendix B**).

The representative concept design cross-sections in **Appendix D** also show typical accreted (2006) and eroded (1974) beach profiles, which indicate that the proposed coastal protection improvement works are expected to be completely buried by beach sand under typical (non-eroded) beach states (see **Section 4.8**).

3.4 Concept Design and Alignment Summary

The concept design cross-sections and alignment for the proposed coastal protection improvement works are expected to result in completed works with a footprint that is generally landward or at most, within +2 m to +3 m seaward of the existing ad-hoc works.

[1] It is noted that where Council elects to rely on existing coastal protection works, a detailed condition assessment and design review Report for the existing structure should be obtained from a suitably experienced coastal engineer.

4. Assessment of Proposed Coastal Protection Improvement Works

4.1 Overview of Assessment

This assessment of the proposed coastal protection improvement works is based on a comparison with the current beach state, inclusive of the existing ad-hoc protection works, their present impacts (which have existing for several decades) and ongoing sand management practices. It draws upon the present understanding of existing coastal hazards and the quantitative coastal processes model (**Figure 6**) developed from existing relevant data and studies as presented in **Section 2**. The overall benefits of the proposed coastal protection improvement works in terms of satisfying contemporary serviceability levels with regards to coastal protection and vastly improved public safety are also discussed.

4.2 Assessment of the Proposed Cross-shore Location of Coastal Protection Improvement Works

The cross-shore location of the proposed coastal protection improvement works (as described in **Section 3**) has been determined by the following principles:

- Located on private land wherever practicable;
- A maintenance corridor of 6 m landward of the primary armour from existing buildings wherever practicable; and
- A structure slope not steeper than 1V:1.5H [(2)], founded on the cemented sand layer where present or else founded at or below -1 m AHD.

The proposed cross-shore location of the works (**Section 3.2**) has been determined through direct feedback between the Engineering Design Consultant, Northern Beaches Council staff and the MHL/WRL assessment team to establish clear priorities between maximising beach amenity, achieving a uniform and practicable alignment and providing adequate access for future repairs and/or future adaptation. The results of this interactive process are as documented in **Appendix C** and **Appendix D**.

It is noted that wherever practicable, more landward locations for the proposed coastal protection improvement works have been effected (for example at Wetherill Street) with the advantages of improved beach amenity derived from increased duration of the works being buried in sand, reduced durations that pedestrian access along the beach would be affected following storm erosion as well as reduced wave forces and wave overtopping during storms (see **Section 4.8** regarding alignment tolerance with respect to beach amenity and **Section 2.2.4** and **Section 4.7** regarding wave overtopping).

[2] Refers to rubble mound rock armoured structures. Alternative to rock structures may be considered subject to structural design, crest level and toe level adjustment by a suitably experienced coastal engineer.

The adopted 6 m maintenance corridor along the crest is considered to be a suitable distance, although this could potentially be reduced slightly based on demonstrated satisfactory access achieved on the Gold Coast, where a maintenance corridor of 4.6 m has been adopted since around 1972 (GCCC, 2013). More landward alignments than this are not considered practicable given existing building lines.

4.3 Consistency with CZMP and Coastal Erosion Policy

The certified Coastal Zone Management Plan for Collaroy-Narrabeen Beach and Fishermans Beach (CZMP, 2014) incorporates details of compliance with the NSW Coastal Management Principles articulated in the NSW Coastal Management Guidelines, the NSW Coastal Protection Act 1979 and the NSW Coastal Policy 1997.

The certified CZMP (2014) aims to provide a balanced management approach that protects and preserves the beach environments while limiting the impact of coastal processes on public and private assets. Community and stakeholder consultation undertaken during the development of the Plan identified key priority issues as maintaining beach amenity and minimising the impacts of coastal processes attributable to development.

Consistent also with the current Draft Northern Beaches Coastal Erosion Policy (NBC, 2016), property owners are described as primarily responsible for carrying out new development on beachfront and near beachfront land adjacent to Collaroy-Narrabeen Beach provided that the risk of damage from coastal processes can be demonstrated to be acceptably low. Property owners (including government) are responsible for protecting their property from the impacts of coastal processes, and are responsible for ensuring their property does not adversely impact on adjoining properties or coastal processes.

Management options deemed to be appropriate for further investigation included, sand recycling and nourishment, dune management, land use planning, the application of development controls and consideration of new or upgraded coastal protective works. The only location where coastal protective works by property owners are considered to be necessary and suitable (provided they manage any offsite impacts and subject to the requirements of the *Environmental Planning and Assessment Act 1979*), is south of Devitt Street at Collaroy-Narrabeen Beach. Protective works at other locations are not considered necessary or suitable based on acceptable risk (see **Figure 5**).

The implementation of consistent and appropriate protective works on Collaroy-Narrabeen Beach is complex and will require co-ordination of the various property owners, consideration of funding and maintenance mechanisms, and detailed design guidance. In recognition of this, one of the highest priority actions in the certified CZMP (2014) is to develop guidelines on the protective works to resolve these issues. This assessment of the proposed coastal protection improvement works has included review of the proposed design standards (**Appendix B**), alignments and required setbacks (**Appendix C** and **Appendix D**).

Subject to the findings of this assessment, which follows, of the proposed coastal protection improvement works with regards to potential impacts on coastal processes, adjoining properties and beach amenity (including a discussion on possible mitigating measures), the proposed works south of Devitt Street are considered to be in general compliance with the requirements of the certified CZMP (2014) and the Draft Northern Beaches Coastal Erosion Policy. It is noted that proposed funding arrangements, detailed design, development consent, sand offsets, construction and maintenance aspects of the CZMP (2014) and Coastal Erosion Policy are not evaluated as part of this assessment.

With regards to public access arrangements, it is considered that ongoing maintenance of existing access arrangements, beach scraping, fencing and appropriate signage as proposed within the certified CZMP (2014) and Coastal Erosion Emergency Action Sub-Plan (2015) following storm erosion are appropriate to ensure continuing and undiminished public access to beaches, headlands and waterways. Ongoing sand recycling from the lagoon entrance and sand nourishment from suitable building sites, as proposed, are both also strongly supported. Additional large scale sand nourishment by government to mitigate possible beach recession effects of projected sea level rise is generally supported as a viable management response should this prove to be necessary.

4.4 Potential Impacts of Seawall Concept Design and Alignment

4.4.1 Physical Impacts of Seawalls Generally

Potential physical impacts of seawalls and shoreline revetments include:

- Altered erosion and accretion seaward of the wall;
- Altered erosion and accretion either side (alongshore) from the wall;
- Altered longer term recession and progradation alongshore from the wall;
- Propensity to form rips;
- Changes to wave run-up and wave overtopping; and
- Changes to surfing amenity.

Not all of these potential physical impacts have been demonstrated and some may only apply to particular situations as discussed with other aspects of seawall impacts on beaches in **Appendix A**. Key findings relevant to the proposed coastal protection improvement works at Collaroy-Narrabeen Beach are outlined in **Section 4.4.3**. For this project, the potential impacts of the proposed coastal protection improvement works have been compared with the existing conditions inclusive of the existing ad-hoc seawalls, rather than with an undeveloped beach.

4.4.2 Socio-Economic Impacts of Seawalls Generally

Seawalls/revetments may also have socio-economic impacts. Positive socio-economic impacts of seawalls may include:

- Provision of additional, improved or more secure public recreational space;
- Improved security to landowners; and

- Changes to property values.

Negative socio-economic impacts of seawalls may include:

- Loss of recreational beach amenity;
- Erosion and/or recession due to off-site (alongshore) impacts of structures; and
- Increased wave run-up and overtopping due to smooth/hard structures.

These and other aspects of seawall impacts on beaches are discussed further in **Appendix A** with key findings relevant to the proposed coastal protection improvement works at Collaroy-Narrabeen Beach outlined below.

4.4.3 Summary and Evaluation of Beach Response to Seawalls

The effect of seawalls on fronting and adjacent beaches remains somewhat unresolved as detailed in **Appendix A** (**Sections A1** to **A4** in particular). While a substantial body of research including laboratory studies and intensive field monitoring programs were undertaken in the late 1980s and early 1990s, consensus was not obtained as to whether seawalls actively promote greater erosion than would otherwise occur without the seawall in place. Much of the controversy is attributed to lack of distinguishing between 'sand entrapment', 'passive erosion' and 'active erosion' (Pilkey and Wright, 1988; Griggs et al. 1991, 1994) as described below.

- Sand entrapment truncates that portion of the active beach behind (or beside) the seawall, denying that volume to the lower (or adjacent) beach but preserving that part entrapped. A corresponding lowering of the fronting beach in times of storm demand is predicted by Dean's 1986 *approximate principle*.
- Passive erosion is defined as being caused by "tendencies which existed before the seawall was in place" and again, a relative seaward movement of the seawall and resultant narrowing of the fronting beach should be expected (Griggs et al., 1994; Pilkey and Wright, 1988). It is analogous to beach recession as defined in this report.
- Active erosion is defined as being "due to the interaction of the wall with local coastal processes" and is the most controversial. Arguments for active erosion of fronting beaches include '*telescoping*' of surf zone processes and inhibition of storm recovery (Pilkey and Wright, 1988). Field studies on both long-term stable beaches (Griggs et al., 1990; 1991; 1994) and on actively eroding coasts (Basco et al., 1992; 1993) found that while beach profiles were typically lowered faster in front of seawalls during storm conditions, there were no substantial long-term differences between sea-walled and non-walled beaches which could not be explained by entrapment and passive erosion. Seawall end effects are well recognised due to turbulence and oblique wave reflection (Tait and Griggs, 1990; McDougal et al. 1987; and others) as discussed separately in Section 4.5.2 (see also **Appendix A**; **Section A5.2**).

Exact and universally-accepted methods for predicting the magnitude and extents of beach response are not yet available. Reasons for this include:

- Wide variation in types and placement of structures;
- The paucity of sites where comprehensive monitoring has been undertaken;
- Variation in antecedent beach morphology which precludes deriving predictive expressions which are applicable over all conditions;
- Difficulty in separating erosion (short term) and recession (long term); and
- High noise, natural variability and three dimensional effects in coastal processes.

The '*approximate principle*' of Dean (1986) suggests that the scour fronting the seawall should be equivalent to the amount of sand entrapped behind the structure as shown in **Figure 8** (after Carley et al, 2013). Kraus (1988) and Sutherland et al. (2007) suggest that the maximum scour depth is related to the offshore wave height (see **Appendix A**, **Section A5.1**; **Figure A3b**).

Laboratory studies of seawall end effects by McDougal et al. (1987) proposed a linear relation between seawall length and the distance and depth of excess end erosion which could be expected following a storm event. These relationships were shown to somewhat over predict the landward extent of erosion and alongshore length caused by longer seawalls in field studies (Griggs et al. 1994; Shand, 2010) and a modification, asymptoting at longer seawall lengths was proposed by Shand (2010) – refer to **Appendix A**, **Section A5.2**.

Seawalls which protrude substantially seaward into the active beach surfzone may induce erosion and recession further downdrift, similar to a groyne, headland or river mouth training wall. For most seawalls, where there is not a high rate of passive erosion (recession) on the updrift side, this groyne effect will eventually equilibrate, since sand build-up on the updrift side will bypass the structure (refer to **Appendix A**, **Section A2.1.2**).

4.5 Assessment of Erosion to the North and Potential "End Effects" for Proposed Coastal Protection Improvement Works at Collaroy-Narrabeen Beach

4.5.1 Literature and Techniques

It is well accepted that seawall structures will cause an "end effect" when they terminate in a sandy foreshore as described by McDougal et.al. (1987) and as experienced at many locations including for example on the Gold Coast in 1967 as shown in **Figure 9**. The proposed engineered coastal protection improvement works at Collaroy-Narrabeen Beach extend southward to existing seawalls fronting the Collaroy Services Beach Club, Collaroy SLSC, Collaroy ocean pool and cliffs. Therefore, for appropriately engineered structures extending from Devitt Street to Collaroy ocean pool, the only potential for an end effect is to the north of Devitt Street.

The total distance from Devitt Street to the southern corner of sand on Collaroy Beach is approximately 2 km, with about 1.7 km to 1.9 km of this occupied by seawalls prior to the proposed new improvement works (there were no engineered seawalls from Stuart Street to Ramsay Street and only partial rock protection works fronting the car park opposite Jenkins

Street prior to June 2016). The full 2 km would be occupied by seawalls after the proposed new works. To the north, the existing and proposed seawalls terminate at Devitt Street. End effects are evident from Devitt Street to the north already, as a result of the existing 1.7 km to1.9 km of seawalls.

Carley et al (2013) analysed international literature on seawalls, together with field data from seven Australian sites. They noted that it is difficult to separate out long term recession from short term erosion. Carley et al (2013) illustrated the importance of the seawall position in the cross shore profile as critical in assessing the impacts of a seawall (**Figure 8**).

The classic work by McDougal et al (1987) (**Figure 9**) indicated that the seawall end effect will extend for 70% of the seawall length, with the maximum additional erosion equal to 10% of the seawall length, however, these amounts are uncapped. Provided that a seawall is not fully emergent into the surf zone (and therefore not acting as a long term groyne/headland), the alongshore extent of the end effect was found to be limited in other studies (**Appendix A**, **Section A5.2**). Other literature and analyses in Carley et al (2013) indicate that where a seawall does not substantially form a long term groyne or artificial headland, the end effect is limited to about 400 m. The additional erosion is highly dependent on the seawall's position on the profile. Carley et al (2013) suggested that the following relationship be used (see **Figure 8** and **Figure 9**):

$$S = 100 + 0.60\ Ls \text{ (maximum } S = 400 \text{ m)} \qquad (1)$$

$$AE = (1 - NDV) * SD \qquad (2)$$

where:

- S is the alongshore extent of end effect as shown in **Figure 9**;
- Ls is the length of the seawall as shown in **Figure 9**;
- NDV is the available sand volume seaward of a seawall divided by the storm demand as shown in **Figure 8**;
- AE is the expected additional erosion (r) as per **Figure 9**; and
- SD storm demand (e) as per **Figure 9**.

4.5.2 Estimate of End Effect for Collaroy-Narrabeen Beach

With a total seawall length (Ls) of 1.7 km to 2 km, the uncapped alongshore end effect distance from McDougal et al (1987) would be 1,400 m. Basic analysis of numerous aerial photos indicates that the end effect north of Devitt Street is apparent to between Robertson Street and Narrabeen Street, a distance of 300 m to 400 m, which is consistent with observations of a capped distance from other locations. Due to the capping limitation, the addition of a further 100 m to 300 m of new engineered seawall to fill gaps within the existing overall extent (without any substantial extension to the north) is not expected to alter the end effect to the north. This seawall gap filling is required to protect the assets presently at risk and to prevent flanking failure of the seawalls on either side of the gaps.

North of Frazer Street, the 100 year ARI storm erosion adopted in the CZMP (2014) is 250 m^3/m above AHD, relative to a typical accreted beach state. Basic analysis of the photogrammetry and profile data between Wetherill Street and the Marquesas indicates that there is typically about 55% (for accreted beach conditions) of this volume seaward of the existing seawalls (NDV). The additional maximum erosion to the north could be a further 45% (as per **Figure 8**) due to the end effect, which would taper to zero additional erosion by about Narrabeen Street.

Application of **Equations (1)** and **(2)** to estimate the seawall end effects during a present day 100 year ARI erosion event for Collaroy-Narrabeen Beach is shown in **Figure 10**. Also shown in **Figure 10** are expected end effect lines where the average seawall alignment is shifted 5 m landward and 5 m seaward of the existing seawall alignment, which is indicated to result in the end effects differing by about 3.5 m from the status quo seawall alignment case.

4.6 Assessment of Impacts of Partial or Ad-hoc Completion of Proposed Coastal Protection Improvement Works

It is recognised that it may not be possible or practicable to construct all of the proposed coastal protection improvement works concurrently over a short duration. Nevertheless, if gaps, ad-hoc or substandard works form part of the upgraded works, flanking failure of the complying structures is possible. Examples of flanking failure and failure of ad hoc works are shown in **Figure 9**.

The additional material and effort required for returns to prevent flanking failure may be comparable to the required frontage for a single allotment. It is recommended, therefore, that works be completed from road head to road head (or to the northernmost point) and that no discontinuous works be permitted between the road heads. Given the proposed landward reconstruction of the coastal protection improvement works at Wetherill Street, it is recommended that these re-location works be undertaken before construction of improvement works is permitted to the south of Wetherill Street.

4.7 Review of Proposed Surface and Stormwater Management Measures

Appropriate drainage design to adequately manage local rainfall runoff and ocean waters resulting from wave overtopping during coastal storms is considered to be critical to the proposed coastal protection improvement works design guidelines. Possible failure modes for seawalls associated with drainage issues include amongst other things, erosion of the backfill (caused by wave overtopping), high water table levels and/or leaching of backfill materials through the seawall (SCCG, 2013).

For porous structures such as rock rubble mound seawalls, this requires correct granular filter layer and geotextile design. For vertical and composite structures, this requires correct drainage design through the structure to avoid excessive hydrostatic forcing and to prevent leaching of material. The proposed seawall design criteria (as amended; **Appendix B**) are generally considered to include appropriate guidance with regards to surface and stormwater management measures.

In relation to the Council reserves for which preliminary concept seawall designs have been prepared, wave overtopping rates have been estimated as detailed in **Appendix A**, **Section A6** and as discussed in **Section 2.2.4**. For the Collaroy Beach carpark north of the Collaroy Services Beach Club, there is a drainage system for the paved carpark which is understood to be adequate to cater for both local runoff and average wave overtopping rates of 13 L/m/s for the 50 years ARI design storm under existing sea level conditions (see **Table A4**). The Engineering Design Consultant has indicated that as there is a limited catchment area seaward of the carpark in the area of the seawall, natural infiltration of both stormwater runoff and wave overtopping flows is relied upon here. The estimated average wave overtopping rate of 208 L/m/s for a projected future sea level rise of 0.9 m (or a design still water level of 2.4 m AHD; **Table A4**) is expected to result in damage to the carpark pavement (based on EurOtop, 2007 guidelines; **Table A3**) unless the proposed seawall design crest level at this location were raised above the presently proposed level of 5.5 m AHD. Notwithstanding this, the landward granular filter layers and geofabric as proposed in the concept design cross-section for this area (see **Figure A7**) is considered to be adequate to prevent any significant structural damage of the seawall itself.

Along the Frazer Street Reserve, the seawall crest level proposed is only 4.5 m AHD see **Figure A8**), with 81 L/m/s average wave overtopping expected during the design storm under present day sea levels with damage to the vegetated reserve area expected. As indicated by the Engineering Design Consultant, this reserve has a significant grade back towards Pittwater Road. Surface runoff would travel to the road drainage system. Natural infiltration is also likely to be significant due to the sandy nature of the soils there. While no specific drainage system is considered to be required by the Engineering Design Consultant for this area, it is noted that significant damage to the parkland would be expected from wave overtopping and raising the seawall crest may be justified on an economic and general public nuisance value perspective. A future seawall adaptation design should nevertheless be incorporated as part of the detailed design for this area given the significant potential damage to Pittwater Road expected under projected future sea level rise conditions with an indicated average storm wave overtopping rate in excess of 870 L/m/s (see **Table A4**).

For the coastal protection improvement works concept design at South Narrabeen SLSC, which has a proposed crest level of 6 m AHD (see **Figure A9**), the indicated average wave overtopping rates are indicated to be acceptable, with damage to existing grassed areas expected only for the projected future sea level rise scenario of 0.9 m (see **Table A4**). Given the relatively high mobilisation costs expected to implement any future adaptation strategy, however, it is recommended to increase the minimum design crest level to 6.5 m AHD for this location unless a lower crest level can be justified using physical model testing as part of the detailed design process. It is noted, also, that the Coastal Erosion Emergency Action Sub-Plan for Collaroy-Narrabeen Beach should be updated to include temporary sand-bagging of the boat ramp at the SLSC as much higher wave overtopping rates would be expected at the ramp. The Engineering Design Consultant has indicated that runoff from all hard surfaces in this area would be expected to drain to Pittwater Road and/or return to sea via natural infiltration. For the indicated average wave overtopping rates, local drainage at the SLSC would not be expected to be significantly affected by the proposed coastal protection improvement works and the existing drainage system is expected to be adequate.

An evaluation of wave overtopping was undertaken also for the existing seawall at Wetherill Street based on a crest level of 6 m AHD (**Figure A10**), indicating that the paved road should not be significantly damaged, even allowing for projected future sea levels, although the road shoulder and surrounds would be expected to suffer damage (see **Table A4**). Given the expected difficulties and costs in implementing future adaptation at road heads, it is recommended that the seawall crest level be increased to a minimum of 6.5 m AHD. As discussed in **Section 2.2.4**, a minimum design crest level of 6.5 m AHD is recommended for all conventional rock rubble mound structures unless justified by site specific factors correctly evaluated as part of the detailed design process. It is recommended also that the seawall design criteria for Collaroy-Narrabeen Beach (**Appendix B**) be revised to include more explicit minimum drainage design criteria comprising a minimum width and depth of granular filter materials and geotextiles.

For non-conventional composite designs or vertical or near vertical structures, higher wave overtopping rates are expected, with resulting higher minimum necessary design crest levels. Structures incorporating explicit design allowances and triggers for future sea level rise adaptation, conversely may be able to adopt lower initial crest levels. For all non-conventional rock structures, it is recommended that physical model testing be undertaken to verify wave overtopping rates, overall stability and the suitability of the proposed works as part of the detail design and approval process.

In addition to the identified local drainage issues, there are 7 primary stormwater outfalls that drain onto the beach along the study area comprising Collaroy Street, Frazer Street, Ramsay Street, Goodwin Street, Albert Street, Tourmaline Street, and Malcolm Street. Catchment areas, flow rates and other details for these outfalls are described in Patterson Britton (1993) with photographs and descriptions also provided in the CZMP (2014). Collaroy Street and Ramsay Street are the most significant outfalls with catchment areas extending well westward of Pittwater Road. Generally individual lots drain to Pittwater Road or have on site infiltration systems. Further consideration will need to be given to the existing outfalls at Frazer Street, Ramsay Street, and Goodwin Street as part of the detailed design of the proposed coastal protection improvement works. As indicated by the Engineering Design Consultant, this will depend on final road head treatments. They also noted that the Goodwin Street outfall was damaged during the June 2016 storm.

As described in the CZMP (2014), some of the existing stormwater outlets also cause localised scour to beach berm and/or dune areas, localised flooding when outlets are blocked with sand, and can be accessed by the public with potential for personal injury. Potential upgrade works proposed in the CZMP (2014) include:

- installation of ‘duckbill’ check valves at outlets to prevent sand ingress;
- installation of surcharge pits to mitigate local flooding caused by buried beach outlets;
- installation of safety screens on outlets to prevent public access; and

- diversion of stormwater discharges away from the beach where possible.

These actions form part of the certified CZMP (2014) and are understood to have been incorporated into Council's Stormwater Asset Management Plan.

4.8 Horizontal Alignment Tolerance and Estimate of Cross-Shore Position of Works on Beach Amenity

Sand levels against the present and future seawall during accreted beach conditions are generally in the range 3 m to 5 m AHD. The future seawall is likely to be founded at 0 m to -1 m AHD. Much of the structure will be below the sand level most of the time.

Typical primary armour rocks for the concept design will have dimensions in the range of 1 m and could be up to 2 m maximum. Therefore, two armour rocks of 2 m could occupy about 4 m horizontally. The initial estimate of the impacts on beach amenity due to the seawall's cross-shore position have been based on ambient wave conditions and an assumed sand level against the seawall. In reality, this would be complicated by the changing sand level and varying wave conditions. This initial estimate is based on the following input components:

- A useable alongshore beach access width of 2 m between the seawall and the wave run-up level R2%;
- A subaerial beach slope of 1V:15H between +1 m and +3 m AHD;
- Mean high water of 0.7 m AHD;
- Ambient wave conditions of H_s = 1.5 m and T_p = 10 s;
- Water level exceedance probabilities from MHL Report 2236 (2013; 2016).

The wave run-up method of Mase (1989) has been tested against numerous Australian run-up events, including the measured run-up levels during the August 1986 storm at Collaroy Narrabeen reported in Higgs and Nittim (1988). Under ambient wave conditions, the R2% wave run-up in the vicinity of Wetherill Street is estimated to extend 1.8 m above the prevailing still water level. That is, if the still water level is 0 m AHD, the R2% wave run-up would reach 1.8 m AHD.

The proportion of time that there would not be 2 m of dry beach (above the R2% run-up level) during ambient wave conditions is shown in **Table 1**. This is based on the measured exceedance of still water level for approximately 88 years at Fort Denison. Note that there would be times with waves larger and smaller than ambient, and differing sand levels against the seawall.

Table 1: Percent of Time Beach would be Impassable during Ambient Wave Conditions

Sand level against wall (m AHD)	Status quo alignment	Wall seaward 2 m	Wall seaward 5 m	Wall landward 2 m	Wall landward 5 m
2.0	49%	56%	72%	42%	27%
2.5	13%	19%	34%	8%	4.6%
3.0	0.3%	1.0%	4.6%	0.1%	0.002%

From **Table 1**, it can be seen that if the sand against the seawall was at +2 m AHD, the beach would be impassable 49% of the time under ambient wave conditions. If the seawall was located 2 m further seaward, this would increase to 56% impassable, and 72% impassable if the seawall was located 5 m seaward from the status quo.

If the sand level against the seawall was at +3 m AHD, the beach would be impassable only 0.3% of the time under ambient wave conditions.

Therefore, unless a moderate beach nourishment program is implemented, it is recommended that the new seawall alignment be as landward as possible. For future upgrades and construction practicality, an alignment tolerance of at least one armour rock is suggested. One armour rock of seaward projection would occupy up to 2 m, which would cause only a small increase in the amount of time the beach would be impassable.

Seaward projections of 5 m or more from the status quo would cause significant increases in the amount of time the beach would be impassable based on this preliminary evaluation. A more detailed probabilistic approach, involving a full time-series simulation of wave run-up levels incorporating a representative long-term historical period of measured ocean water levels and waves is expected to provide more realistic results.

4.9 Assessment of the Visual Amenity of the Proposed Coastal Protection Improvement Works

Apart from the stretch of foreshore from Ramsay Street to Stuart Street (110 m), seawalls are already present along the entire study area. Compared to the status quo, the coastal protection improvement works are proposed to be on a similar alignment, would have a crest below the land levels landward of it and would have a similar proportion of visual exposure (during eroded beach states). Due to a more engineered construction (as is necessary to be effective), the representative rock rubble concept design would have a more regular appearance and contain less detritus and small rubble than the existing ad-hoc works. Most of the time, the majority of seawalls will be buried in sand and/or vegetation. Therefore, the visual amenity of the proposed concept design will be substantially unchanged during average and accreted beach conditions, and would be improved in terms of uniformity of appearance during eroded beach conditions.

4.9.1 Tenacity Consulting versus Warringah Council Case Study

The most commonly cited work on the planning context of views in NSW is Tenacity Consulting versus Warringah Council (2004; NSWLEC 140). Commissioner Rosen listed four principles in the assessment of views, view loss and view sharing, though this was primarily from the perspective of views from buildings and the impact of new development upon them.

The commissioner listed the following principles:

> *"25. The notion of view sharing is invoked when a property enjoys existing views and a proposed development would share that view by taking some of it away for its own enjoyment. (Taking it all away cannot be called view sharing, although it may, in some circumstances, be quite reasonable.) To decide whether or not view sharing is reasonable, I have adopted a four-step assessment.*
>
> *26. The first step is the assessment of views to be affected. Water views are valued more highly than land views. Iconic views (eg of the Opera House, the Harbour Bridge or North Head) are valued more highly than views without icons. Whole views are valued more highly than partial views, eg a water view in which the interface between land and water is visible is more valuable than one in which it is obscured.*
>
> *27. The second step is to consider from what part of the property the views are obtained. For example the protection of views across side boundaries is more difficult than the protection of views from front and rear boundaries. In addition, whether the view is enjoyed from a standing or sitting position may also be relevant. Sitting views are more difficult to protect than standing views. The expectation to retain side views and sitting views is often unrealistic.*
>
> *28. The third step is to assess the extent of the impact. This should be done for the whole of the property, not just for the view that is affected. The impact on views from living areas is more significant than from bedrooms or service areas (though views from kitchens are highly valued because people spend so much time in them). The impact may be assessed quantitatively, but in many cases this can be meaningless. For example, it is unhelpful to say that the view loss is 20% if it includes one of the sails of the Opera House. It is usually more useful to assess the view loss qualitatively as negligible, minor, moderate, severe or devastating.*
>
> *29. The fourth step is to assess the reasonableness of the proposal that is causing the impact. A development that complies with all planning controls would be considered more reasonable than one that breaches them. Where an impact on views arises as a result of non-compliance with one or more planning controls, even a moderate impact may be considered unreasonable. With a complying proposal, the question should be asked whether a more skilful design could provide the applicant with the same development potential and amenity and reduce the impact on the views of neighbours. If the answer to that question is no, then the view impact of a complying development would probably be considered acceptable and the view sharing reasonable."*

4.9.2 Other Studies regarding Visual Amenity

There have been a number of studies which have explored the relative preferences for protective structures and natural shorelines, as described below. Generally, visitors and residents prefer a more natural appearance and hence seek out accommodation near unaltered shorelines. This translates into a *willingness to pay* (WTP) to avoid protective structures, or to seek out more natural coastlines. It should be noted that the impact appears to be linked almost entirely to whether the structure is visible. There are many locations within Australia, particularly in Sydney and the Gold Coast, where a seawall structure is present but generally obscured by an overlying dune. This dune has typically been placed artificially, yet is covered by natural vegetation. Sand nourishment/recycling schemes are also employed at some of the most highly visited beaches, in order to maintain a 'natural' appearance of the shoreline and provide a sandy beach seaward of the seawall.

In the UK, analysis of property values by real estate agency Knight Frank suggests that vision of an estuary is considered to be more valuable than vision of the ocean, possibly due to changes caused by tidal variation. Further research would be necessary to determine if this was the case in Australia, but the price premiums for water views were:

- Estuary 82%
- Harbour 81%
- Riverside 53%
- Coastal 47%
- Lakeside 36%

The relationship between the quality of the view and the relative price premium is identified in the majority of studies attempting to place values on the presence of pleasant or unpleasant views. The relative *willingness to pay* (WTP) for a partial view differs between published studies.

Pearson et al. (2002) found that a full unobstructed view of the ocean near Noosa resulted in a price premium of 76%, indicating a strong preference for ocean views. Unfortunately from the perspective of this analysis, partial view coefficients were not statistically significant.

It is difficult to separate the benefits of ocean views from other non-aesthetic coastal amenities, however, particularly given that the benefit of a distant view has been shown to be less than that of a closer view of the same quality (Benson, Hansen et al. 1998).

In simple terms, this means that in an area dominated by low-rise buildings, the majority of the benefits of a pleasant view accrue to the properties along the beachfront, but it is difficult to know how much of the price premium paid for these properties is due to the view itself rather than other factors such as direct or proximate beach access, prestige value or other unidentified components. There have been highly technical attempts (Bin, Crawford et al. 2008; Hamilton and Morgan 2010) to value minor changes in view angle, down to a one degree variation, although this is unlikely to be a measure that relates to real world purchasing decisions.

4.9.3 Summary and Synthesis of View Impacts in Relation to the Proposed Coastal Protection Improvement Works for Collaroy-Narrabeen Beach

Most studies and cases regarding views involve buildings and property values. Views of the water are considered to be the most valuable and iconic. The proposed works will be on a similar alignment to the existing ad-hoc seawalls and will generally not extend beyond the existing natural ground levels at the dune crest.

It may be reasonably concluded, therefore, that:

- the proposed works will not adversely impact views from private properties;
- the proposed works will not adversely impact views of the water from the beach and other public lands;
- the proposed works may change the view from the beach when looking landward, but this is likely to be somewhat improved from the existing condition, due to a more regular structure and less small material and detritus.

Regarding the visual amenity of the proposed coastal protection improvement works, it is concluded that the overall impacts compared with the status quo will be positive and providing an indifferent or improved visual amenity.

4.10 Evaluation of Serviceability and Public Safety of the Proposed Coastal Protection Improvement Works

The existing ad-hoc coastal protection works have been well demonstrated to not meet conventional coastal engineering standards (MHL, 1999, PB&P, 2001, Cameron, 2010, CZMP, 2014), with extensive damage to buildings, property and the structures themselves experienced during historical coastal storms since the early 1960s. The existing ad-hoc works present significant public hazards, particularly immediately following major erosion events, when large rock overhangs and unstable substrata are exposed, with risk of collapse, and severely limit public beach access. Due to the serviceability and access limitations, and the significant public hazards presented, further ad-hoc emergency repairs (often funded under the public purse) have taken place over the past decades, representing poor public value for money.

The proposed coastal protection improvement works will be designed and constructed to meet conventional coastal engineering standards, and while some damage may still be expected during major coastal storm events beyond the adopted design conditions (**Appendix B**), this is expected to be in a far more controlled and acceptable/planned manner. The proposed coastal protection improvement works, therefore, are expected to provide vastly improved public access (because there is much less risk of rocks collapsing onto the beach during a storm) with an alignment established to maximise the public beach amenity as far as practicable in comparison to the existing ad-hoc works. Construction of the improvement works will provide an opportunity to cost effectively remove any strewn rocks dislodged from the ad-hoc works onto the public beach, thereby improving public safety.

4.11 Evaluation of Potential Mitigation Measures

While no significant discernible adverse impacts have been identified on existing coastal processes or amenity values for the proposed coastal protection improvement works compared with the existing situation, there are a number of potential measures that are evaluated in terms of further improving beach amenity values and assisting natural coastal processes in recovering from the impacts of coastal storms.

Potential mitigation measures considered here comprise:

- beach scraping to accelerate natural beach recovery and improve beach access;
- minor to moderate beach nourishment to increase average beach width for amenity purposes;
- large scale (regional) sand nourishment;
- a promenade/walkway to provide uninterrupted alongshore access and/or improved alongshore access provisions;
- alternative seawall cross sections; and
- Construction of groynes or artificial headlands to compartmentalise the beach and enhance surfing.

Groynes or artificial headlands are not part of the certified CZMP (2014) and given the extensive evaluation of management options already undertaken involving professional inputs and public consultation, this measure is not evaluated further here. A promenade / walkway is not part of the proposed concept design as this would involve additional complexity and coordination for construction, and potentially significant additional cost. While public foreshore pedestrian access is valued by the local community, the present level of amenity is assumed to be satisfactory given that improved public alongshore access was not identified as part of the extensive community consultation undertaken as part of the certified CZMP (2014). It is noted that incorporation of alongshore public access within the proposed coastal protection improvement works could result in a more seaward alignment of the structure with reduced sandy beach amenity. The proposed coastal protection improvement works are unlikely to have a discernible impact on alongshore public pedestrian access provided that the seaward encroachment beyond the existing rock structures does not exceed nominally +2 m (**Section 4.8**). The existing public beach accessways have been assessed to be adequate in the certified CZMP (2014) and these are maintained by Council as part of the active Coastal Erosion Emergency Action Sub-Plan (2015). The only additional potential mitigation measures, therefore, are beach scraping, sand recycling (from lagoon entrance clearing) and sand nourishment (from suitable building sites and other potential larger scale/regional operations such as from inner-shelf sand bodies). All existing sand management practices have already been discussed and are strongly supported to continue. Additional large scale sand nourishment should be pursued whenever a need or cost effective opportunity arises.

5. Conclusions and Recommendations

Collaroy-Narrabeen Beach is characterised as having the most highly capitalised shoreline in the Northern Beaches of Sydney and is also classified as the most at risk from coastal processes in NSW and the third most at risk nationally. The main cause of the existing coastal hazards is that development has taken place well within the active coastal zone (within the primary foredune area). The CZMP for Collaroy-Narrabeen Beach and Fishermans Beach was adopted by Council in October 2014 and certified by the NSW Government in November 2015. This plan establishes a framework through which both beaches are managed for current and future generations.

While recognising the need to protect and preserve the amenity and natural values of Collaroy-Narrabeen Beach and Fishermans Beach, the CZMP also recognises that properties adjoining Collaroy-Narrabeen Beach have been adversely impacted by severe coastal storms in the past and are presently exposed to coastline hazards including erosion and inundation from wave overtopping. The CZMP recognises also that existing protection works have been constructed in an ad-hoc manner and have generally been undertaken without proper engineering design. For management of the coastal erosion hazards, the only location where coastal protective works by property owners are considered to be necessary and suitable (provided they manage any offsite impacts and subject to the requirements of the Environmental Planning and Assessment Act 1979), is south of Devitt Street at Collaroy-Narrabeen Beach (see **Figure 5**). Protective works at other locations are not considered necessary or suitable at this time.

In September 2016, Northern Beaches Council engaged an Engineering Consultant (Royal HaskoningDHV) to prepare a concept design and conceptual alignment for about 1,350 m of improved protection works from the north-east corner of the Collaroy Services Beach Club (chainage; Ch 0 m) in the south, up to Devitt Street (Ch 1,337 m) in the north. The proposed coastal protection improvement works are to be designed and constructed for design conditions with a minimum Average Recurrence Interval of 50 years and a design life of at least 60 years. Wetherill Street (Ch 785 m), which delineates the boundary between Collaroy and Narrabeen, represents the most seaward position of the existing ad-hoc structures relative to the normal high water mark and is where the beach is narrowest under typical (not eroded) conditions.

The NSW government's professional specialist advisor, Manly Hydraulics Laboratory (MHL) in association with UNSW Australia's Water Research Laboratory (WRL) was engaged by Northern Beaches Council to review the concept design and concept alignment of the proposed coastal protection improvement works and to assess their expected impacts on coastal processes and beach amenity relative to the present situation. The methodology adopted, findings and recommendations arising from that review are summarised below.

Approximately one third of beach front properties at Collaroy-Narrabeen Beach are at a high or very high risk of damage from coastal erosion. These properties reside between Devitt Street and the Collaroy Services Beach Club. Three hundred and seventy seven (377) beachfront addresses comprising mostly private residential dwellings and high rise apartments as well as the Collaroy Services Beach Club, the South Narrabeen SLSC, public carparks and public recreational areas are affected by coastal hazards.

This assessment of the proposed coastal protection improvement works has been based on a comparison with the current foreshore state, inclusive of the existing ad-hoc protection works, their present impacts (which have existed for several decades) and ongoing sand management practices. It has drawn upon the present understanding of existing coastal hazards and a quantitative coastal processes model as illustrated in **Figure 6**, which has been developed from existing relevant data and studies. The overall benefits of the proposed coastal protection improvement works in terms of satisfying contemporary serviceability levels with regards to coastal protection and vastly improved public safety have also been discussed.

To best understand the present day coastal processes operating along Collaroy-Narrabeen Beach, it is important to understand the geological history of the NSW coastline, the broader regional scale sediment dynamics and the key physical processes responsible for the present form of the Sydney Northern Beaches Coastal Sediment Compartment, the wider Sydney Primary Coastal Sediment Compartment (**Figure 1**) and the Collaroy-Narrabeen Beach Sub-Compartment (**Figure 2**).

During the post glacial rise in sea level, onshore (transgressive) transport of sediment from large sand bodies offshore occurred between the bedrock controlled valleys of the Cumberland Plain to form Sydney's present pocket beaches. This onshore transgression slowed over the more recent stable Holocene epoch (last 6,000 years) as Sydney's beaches aligned to the dominant incident wave energy from the SSE direction. Narrabeen Lagoon was formed as the beach system developed during the post glacial transgression to form the existing foredune barrier and cut off existing creek valleys and the low lying area which now interacts with the ocean through the lagoon entrance at North Narrabeen.

Sydney's beaches are characterised by a series of prominent Hawkesbury sandstone and Narrabeen Group outcropping headlands which largely contain sediments within these major features. Only following rare and sporadic major or extreme coastal storms, able to transport sediments sufficiently offshore, do littoral sediments bypass these headlands to neighbouring compartments via onshore transport under calmer shore oblique waves. The sandy beaches along Sydney's Northern Beaches are dynamic with storm events, but are generally stable features over the long term.

The main physical coastal processes (erosive and accretionary) relevant to Collaroy-Narrabeen Beach (as described in **Section 2)** have been summarised using a Quantitative Coastal Processes Model as illustrated in **Figure 6**, and summarised as follows using the following sediment budget related colour coding:

- ⇨ Sediment budget process sources (additions) are depicted as **+bold green**;
- ⇨ Sediment budget process sinks (losses) are depicted as -underlined red; and
- ⇨ Balanced or neutral sediment budget processes are depicted as *italic grey*.

- Inner Continental Shelf interaction (**< approx. +2,000 m^3/y**);
- Net longshore sediment transport (-10,000 to -30,000 m^3/y; mostly into lagoon);
- Lagoon entrance dynamics (see *longshore transport and entrance management*);
- Cross-shore sediment transport (< *approx. ±840,000 m^3*);
- Headland bypassing (**+0 m^3/y @Long Reef Point**, *±2,000 to ±10,000 m^3/y @Narrabeen Head* and <approx. -2,000 m^3/y @Turimetta Head);
- Fluvial sediment inputs and deposition (*approx. ±0 m^3/y*);
- Aeolian transport (*approx. ±0 m^3/y*);
- Entrance management (**+15,000 to +25,000 m^3/y** anthropogenic sand recycling);
- Building sites (**+2,000 to +3,000 m^3/y** anthropogenic sand nourishment);
- Incidental Removal (-150 to -400 m^3/y anthropogenic); and
- Sand grain size abrasion and headland weathering (*approx. ±0 m^3/y*)

The above sediment budget indicates that onshore transport of inner-shelf sand, although small in the scale of other cross-shore and longshore processes, has the potential to balance the expected long-term sand losses attributable to post storm headland bypassing and potentially also to assist natural beach transgression in response to present and projected future sea level rise. There is no evidence that Narrabeen Lagoon or the existing stormwater drains provide any significant net contribution of sand sized material to the beach and the only relevant interaction between the Lagoon and beach sediments is associated with the flood tide delta (a temporary sediment sink – see **Figure 6** and Lagoon entrance dynamics above). No significant net loss of sand from the beach occurs by aeolian processes (**Figure 6**) as Council periodically sweeps this material back onto the beach.

The careful management of the lagoon's entrance (by recycling an average of +10,000 to +25,000 m^3/y of sand every 3 years to 5 years) and the extra sand nourishment undertaken from building sites (averaging 2,000 to 3,000 m^3/y) have helped maintain and even prograde the finely balanced sediment budget of Collaroy-Narrabeen Beach as supported by historical aerial photogrammetry showing beach accretion of 0.1 m/year from 1951 to 2006 and more recent beach survey data from 1976 to 2008 showing a volumetric accretion of about +0.5 m^3/m/year.

Because the Collaroy-Narrabeen Beach embayment is essentially a stable closed system, the most significant processes in terms of beach fluctuations and shoreline alignment are cross-shore and longshore sediment transport, including the alongshore variability in onshore and offshore sand movements and the time for beach recovery following major storms.

Rapid rates of offshore sand transport are experienced during storms, ranging from -2 m^3/m/h to -40 m^3/m/h. Beach recovery rates are much slower, typically ranging from +0.01 m^3/m/h, up to +0.06 m^3/m/h (equivalent to approximately 0.2 m^3/m/day up to 1.5 m^3/m/day). These rates correspond to complete beach erosion taking place over a matter of hours or days and beach recovery typically taking place over 3 months to two or more years. Despite its significant effects, it is noteworthy that the June 2016 storm event was characterised by a total erosion volume (400,000 m^3) of less than half of the upper bound limit of storm demand estimated that could occur for a series of successive multi-directional storms. For this event, the eroded beach is expected to recover in no less than 90 days and over as much as about 640 days based on historically recorded beach recovery rates.

The quantitative review undertaken in this study of the Collaroy-Narrabeen Beach coastal processes validates the contemporary understanding that the main cause of the existing coastal hazards is that development has taken place within the active coastal zone. The process understanding developed provides some confidence to the assessment of the likely impacts of the proposed coastal protection improvement works on the coastal processes and beach amenity of the study area.

The scope of this review includes also consistency checks with the adopted CZMP and Coastal Protection Policy, consideration of physical and socio-economic impacts of seawalls, evaluation of the expected beach response to the proposed improvement works, an assessment of the expected erosion to the north and potential seawall "end effects", an assessment of potential impacts of partial or ad-hoc completion of works, a review of the proposed surface and stormwater management measures, horizontal alignment tolerances and estimated cross-shore position impacts on beach amenity, potential mitigation measures, visual amenity, potential impacts on local views and expected improvements in overall serviceability, access and public safety.

The concept design cross-sections and alignment for the proposed coastal protection improvement works are expected to result in completed works with a footprint that is generally landward or at most, within +2 m to +3 m seaward of the existing ad-hoc works. The representative rock armour concept design cross-sections are expected to be completely buried by beach sand under typical (non-eroded) beach states. The adopted 6 m maintenance corridor along the crest is considered to be a suitable distance, although this could potentially be reduced to 4.6 m and still provide satisfactory access based on Gold Coast experience. More landward alignments than this are not considered practicable given existing building lines.

A minimum design crest level of 6.5 m AHD should be adopted for conventional rock rubble mound armour designs to satisfy EurOtop (2007) recommended average wave overtopping limits, including consideration for future sea level rise and allowing for some albeit minor damage to foreshore areas, dwellings and infrastructure. Higher minimum seawall crest elevations are likely to be required for alternative and/or composite seawall designs, where vertical or impervious elements are included. Lower initial design crest levels could be adopted where adequate allowance is made for future raising of the crest to adapt for sea level rise projections given that development types and setback distances vary, and the existing foreshore elevation varies from about +4.5 m AHD (towards the south) to above +7.0 m AHD (in the north).

The proposed works south of Devitt Street are considered to be in general compliance with the requirements of the certified CZMP (2014) and the Draft Northern Beaches Coastal Erosion Policy. It is noted, however, that proposed funding arrangements, detailed design, development consent, sand offsets, construction and maintenance aspects of the CZMP (2014) and Coastal Erosion Policy are not evaluated as part of this assessment.

With regard to public access arrangements, it is considered that ongoing maintenance of existing access paths, beach scraping, fencing and appropriate signage following storm erosion (consistent with Council's existing practices) are appropriate. Ongoing sand recycling from the lagoon entrance and sand nourishment from suitable building sites, as proposed, are both also strongly supported. Additional large scale sand nourishment by government to mitigate possible beach recession effects associated with projected sea level rise is generally supported as a viable management response should this prove to be necessary.

The visual amenity of the proposed concept design is expected to be effectively unchanged most of the time when the proposed improvement works are buried in sand. Following storms, the visual amenity would be improved in terms of uniformity of appearance, access and public safety. It is concluded that the overall visual impacts compared with the status quo will be positive.

The proposed coastal protection improvement works will be designed and constructed to accepted engineering standards, and while some damage may still be expected during major coastal storm events beyond the adopted design conditions, this is expected to be in a far more controlled and acceptable/planned manner. The proposed coastal protection improvement works, therefore, are expected to provide improved public access and vastly improved serviceability and public safety (removing overhangs and rocks strewn on the beach) with the proposed alignment established to maximise the public beach amenity as far as practicable in comparison to the existing ad-hoc works.

The overall finding of this review of the proposed coastal protection improvement works for Collaroy-Narrabeen Beach is that no discernible adverse impacts have been identified on existing coastal processes or amenity values compared with the existing situation. The overall benefits of the proposed coastal protection improvement works in terms of satisfying contemporary serviceability levels with regards to coastal protection and vastly improved public safety have also been discussed.

It is recommended generally that the proposed coastal protection improvement works be aligned as far landward as practicable. Based on a preliminary and approximate only analysis, an alignment tolerance of no more than about +2 m seaward of the existing ad-hoc works is recommended, based on this resulting in no expected discernible incremental impacts on alongshore beach access relative to the status quo. Seaward projections of more than +2 m are expected to cause significant increases in the amount of time the beach would be impassable based on this preliminary evaluation. A more detailed probabilistic approach, involving a full time-series simulation of wave run-up levels incorporating a representative long-term historical period of measured ocean water levels and waves is strongly recommended. This more realistic analysis would provide the expected percentage of lost amenity time for different seawall alignments, and could potentially indicate an alignment more seaward than +2 m to be acceptable for some locations.

It is recommended also that all existing sand management practices comprising entrance sand recycling and building site sand nourishment be continued. Additional large/regional scale sand nourishment should be pursued if a need or cost effective opportunity arises.

Other recommendations arising from this review relating to the detailed design of the proposed coastal protection improvement works comprise:

- taking into account sensitivity analysis of the design nearshore water level based on wave setup, including the truncation of the surfzone with a seawall (and therefore the full quantum of wave setup on a dissipative beach not being realised);
- the consequences of potential scour below -1 m AHD where it is physically possible;
- assessing the consequences of 1 hour duration design wave conditions in terms of checking the stability and expected damage to proposed improvement works;
- utilising the NSW nearshore wave transformation tool to check design wave conditions;
- taking into account storm wave overtopping discharge rates and local rainfall runoff drainage;
- checking site-specific factors when confirming the final design crest level, including the capability of the local drainage system, nature of buildings (value and construction materials) and proximity of these and other assets landward of the proposed improvement works – structures incorporating explicit design allowances and triggers for future sea level rise adaptation may be able to adopt lower initial design crest levels;
- physical model testing to verify wave overtopping rates, overall stability and the suitability of any proposed non-conventional rock rubble mound structures;
- provide more explicit guidance on correct granular filter layer, drainage and geotextile design to manage design wave overtopping rates and avoid excessive hydrostatic forcing, comprising a minimum width and depth of granular filter materials and geotextile details; and
- If Council were to allow any owners to rely on any existing coastal protection works, it is strongly recommended that a detailed condition assessment and design review report for the relevant existing structures be obtained from a suitably experienced coastal engineer.

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