Option Analysis Report

Coastal Inundation Risk Analysis - Closed Landfill Sites

Cairns Regional Council

4 December 2023

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ABBREVIATIONS

ACM	Asbestos Containing Material
AEP	Annual Exceedance Probability (%)
AHD	Australian Height Datum. Unless specified otherwise, all datums are AHD in this report.
ARI	Average Recurrence Interval (years, ARI=1/AEP)
BHC	Benzene hexachloride
BOM	Bureau of Meteorology
CCL	Compacted Clay Liner
CRC	Cairns Regional Council
DES	Department of Environment and Science
EA	Environmental Authority
EPA	Erosion Prone Area (coastal erosion)
ERA	Environmentally Relevant Activity
GLC	Geosynthetic Clay Liner
GPS	Global Positioning System
HAT	Highest Astronomical Tide
HDPE	High Density Polyethylene
Hs	Significant wave height
LAT	Lowest Astronomical Tide
LFG	Landfill Gas
LGA	Local Government Area
LST	Longshore Sediment Transport
LTA	Long-Term Average
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MSES	Matter of State Environmental Significance
MSL	Mean Sea Level
SCADA	Supervisory Control and Data Acquisition
SLR	Sea Level Rise (coastal inundation)
STL	Storm Tide Level (coastal flooding)
Tp	Wave peak period modelled as Spectral Peak Period, i.e., Tmm,0-1
USACE	United States Army Corps of Engineers

DEFINITIONS

This report has been developed with technical definitions specific to the risk management of closed landfill sites located on the coast.

Term	Definition
Astronomical Tide	The astronomical tide is the normal day-to-day rising and falling of ocean waters in response to the gravitational influences of the sun and the moon.
Cap failure	Cracks and potholes may cause breaches and depressions on the landfill's surface. Landfill material density is low. Gas and freshwater water may vent, lift, seep-out and displace the landfill cap through piping, cracking, and potholes.
Coastal erosion	Erosion of the shoreline occurs due to wave-breaking actions and loose soil. The erosive forces would often be concentrated on a perimeter bund erosion around the closed landfill site.
Coastal flooding	Episodic coastal flooding due to storm events and cyclone. Coastal flooding includes the effect of storm tide (storm surge plus astronomical tide), wave set-up and wave run-up and overtopping.
Coastal inundation	Long-term coastal inundation due to permanent tidal incursion of the Highest Astronomical Tide (HAT) seawater on land due to on-going of sea level rise.
Landfill Gas	Closed landfills can produce gas for decades. This includes carbon dioxide and methane, which are Greenhouse Gas. Also, toxic organic compounds such as benzene hexachloride (BHR) are often emitted, usually found in petroleum products, insecticides and municipal waste. The collection and burning of the gas via flaring (controlled burning of gas) reduces the climate impact of landfill gas.
Leachate	Liquid produced by landfill sites may include high ammonia and toxins (such as mercury). A liner is often installed to reduce the risk of release of leachate in groundwater, and leachate can be collected around the landfill site to avoid contamination of stormwater. Ammonia nitrifies to produce nitrate when exposed to the environment, and this can damage the ecosystems by eutrophication, where dissolved oxygen in the water is low.
Overtopping	Overtopping discharge occurs due to waves running up a structure's face. If wave run-up levels are high, enough water can reach and pass over the crest of the structure. The overtopping rate is a mean overtopping discharge, given in L/s per metre of defence, which is an average quantity of water passing over the crest during a storm event. Wave overtopping does not describe how many waves overtop the structure and how much water overtop for each wave. Individual wave overtopping flows may be up to 100 times larger than the average overtopping quantities.
Scour	Scouring is related to abrasion of surfaces due to hydraulic actions. Typically scour manifests over submerged areas of the closed landfill cap.
Sea level rise	Sea level rise is defined as an increase in the mean water level due to an increase in the volume of water and thermal expansion of the oceans.
Significant wave height	The significant wave height (Hs) is the average wave height (trough to crest) of the one-third largest waves.

Term	Definition
Storm surge	Non-periodic variations from the astronomical tide are typically associated with the effect of wind on sea level. This increase in the ocean water level is caused by the severe atmospheric pressure gradients (barometric surge component) and the high wind shear induced on the surface of the ocean (wind setup component) by a severe storm or tropical cyclone. The storm surge magnitude depends upon several factors, such as the intensity of the storm, its overall physical size, the speed at which it moves, the direction of its approach to the coast, and the bathymetry and topography of the coastal zone.
Storm tide level	The storm tide level is the peak water level during a storm event, including storm surge and astronomical tide.
Wave peak period	The wave peak period (Tp) is associated with the most energetic waves in the total wave spectrum.
Wave set-up	The strong winds associated with severe storms generate waves. As these waves propagate into shallow coastal waters, they shoal and break as they interact with the seabed. The dissipation of wave energy during the wave-breaking process increases the water level shoreward of the wave breaking point; this effect is the wave setup. Wave set-up piles up of water against the shoreline because of breaking waves.
Wave run-up	Wave run-up is the vertical height above the local still water level up to which incoming waves will rush when they encounter the land/sea interface. The level to which waves will run up a natural foreshore (or a structure) depends on the incident wave parameters and the land boundary's porosity, slope, extent, and configuration. For example, the wave run-up on a gently sloping beach differs from wave run-up on a near-vertical concrete seawall. Wave run-up heights and levels also change on a wave-by-wave basis.

In this report, the following direction conventions have been used:

- Winds and waves: "coming from"
- Currents and sediment transport: "moving towards"

1 INTRODUCTION

Cairns Regional Council (CRC) engaged Water Technology to prepare a coastal inundation risk analysis for ten closed historical landfill sites across the Local Government Area (LGA). These closed landfill sites are adjacent to estuarine waterways or near the open coast. Some of these sites are already at risk of storm tide hazards.

The purpose of this project is to enable CRC to better understand potential public health and environmental risks from closed and historic landfill sites that may be affected by rising water levels through storm surge events or tidal inundation associated with climate change. This report will assist CRC in determining actions to help inform future risk needs for managing these types of assets and to plan for future budget requirements for asset improvements over a long-term time horizon.

This project has been identified as a priority activity in the CRC Coastal Hazard Adaption Strategy (CHAS) "Our Cairns Coast" and has attracted co-funding through the Local Government Association of Queensland (LGAQ) QCoast 2100 grant program.

1.1 Coastal landfill history

The Cairns closed landfills have formed over recent decades as the region developed and landfill management practices evolved. Some landfill sites were closed decades ago, and their extent and content are not well documented. In contrast, the Portsmith landfill site has been subject to sophisticated operational procedures, ongoing monitoring, and environmental management to mitigate waste toxicity. The Portsmith site alone contain 1.7 million m^3 of waste and was operational from 1984 to 2009, when the Portsmith landfill was closed.

Figure 1-1 shows the operational timeline on a Gantt Cart of the Cairns coastal landfills from opening to closing, reconstructed from the analysis carried-out in this study.

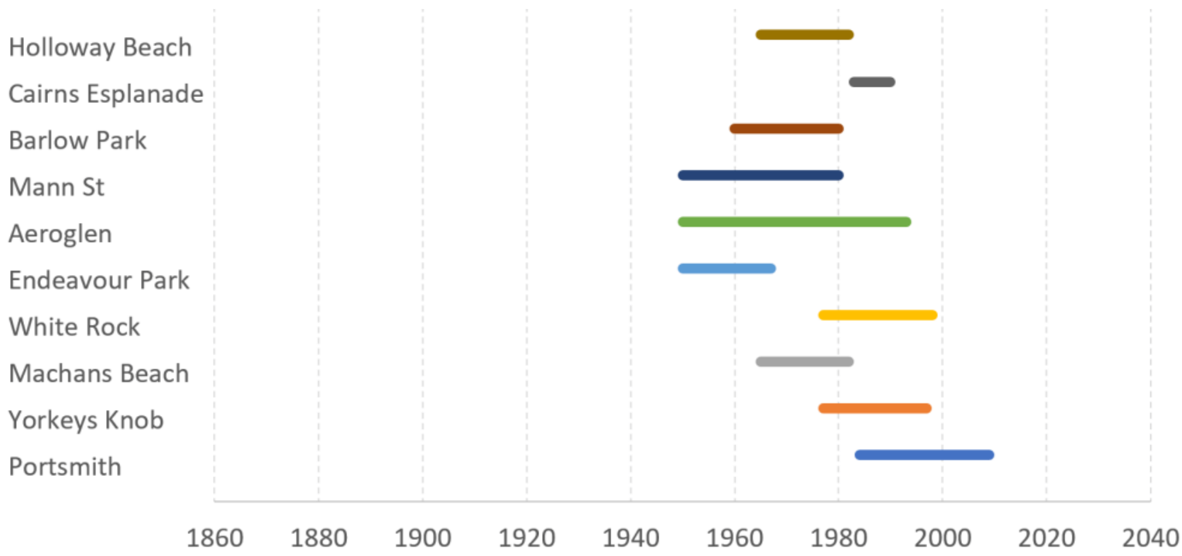

Figure 1-1 Coastal landfill operation

1.2 Landfill volume quantification

Water Technology estimated the total mass of landfill material accumulated in the Cairns LGA from 1885 to 2009 using two methods.

First, an estimate of total solid waste generated across the Cairns urban region was prepared from the Cairns population statistics of the Australian Bureau of Statistics (ABS), using an average landfill rate of 650 tonnes per person. The Cooperative Research Centre (CRC) Waste Reduction and Recycling Strategy and the CRC Internet site waste collection statistics show that the average collected solid waste averages 650 tonnes per capita from 2013-2020. In comparison, the World Bank provided an estimated 590 tonnes per capita in Australia in 2011. The landfill rate per capita would have fluctuated over-time.

A second method consists of calculating the cumulative landfill volume across the ten study sites, assuming an average in-situ dry density of 1.0 tonnes per m^3. While some landfill sites may be missing and the landfill volume could be larger, this provides a lower bound. Landfill waste in-situ dry density can fluctuate between 0.6 and 1.4 tonnes per m^3.

Both methods estimate the combined landfill waste to be approximately 2.7 million tonnes from 1885 to 2009. This estimate is likely to be conservative as other landfill sites may have been used during that period, and the average waste collection statistics per capita for 2013-2020 is likely to have increased, compared to the 1885-2009 period.

Portsmith alone constitutes about 60% of the total mass of coastal landfill. Figure 1-2 shows the cumulative coastal landfill mass across all sites and the estimated total solid waste generated based on ABS population data.

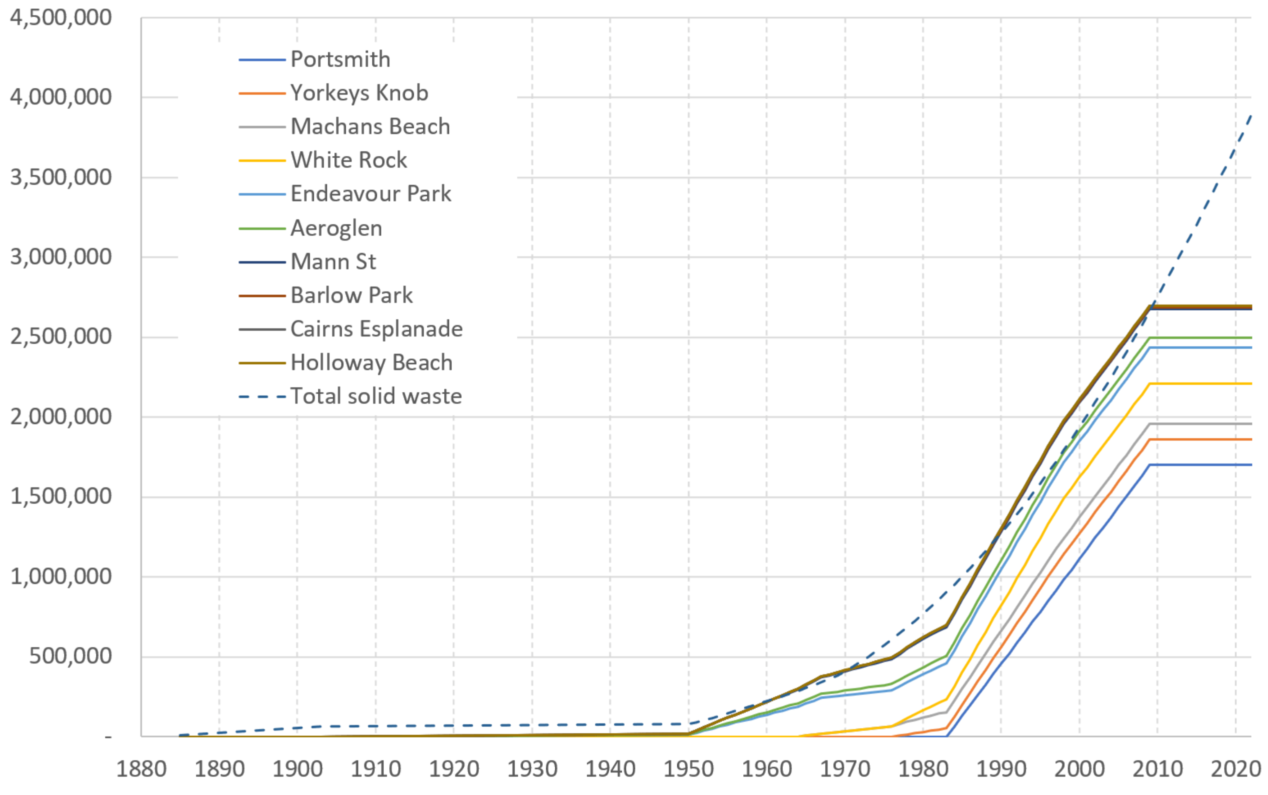

Figure 1-2 Coastal landfill capacity, tonnes

2 SITE DESCRIPTIONS

The ten closed coastal landfill sites within the Cairns Regional Council area investigated were as follows:

1. Portsmith closed landfill – Recovery Way, Portsmith
2. Yorkeys Knob closed landfill (now Half Moon Bay Golf Club) – Wattle St, Yorkeys Knob
3. Machans Beach closed landfill (now Trinity Barron Sports Club) – Marshall St, Machans Beach
4. White Rock closed landfill – Sheehy Rd, White Rock
5. Endeavour Park sporting fields – Cannon St, Manunda
6. Aeroglen Sporting fields – Aeroglen Drive, Aeroglen
7. Mann St Sporting Fields – Mann St, Westcourt
8. Barlow Park Sporting fields – Scott St, Bungalow
9. Cairns Esplanade foreshore park
10. Holloway Beach Landfill Site – Acacia Street

Figure 2-1 shows the location of these sites across the study area.

Figure 2-1 Study Area

2.1 Closed landfill site overview

2.1.1 Portsmith closed landfill – Recovery Way, Portsmith

The Portsmith Closed Landfill is located at the end of Recovery Way, Lot 17 SP 270880 (Land Lease). The site area is 21.51ha with an estimated waste volume of about 1.7 million m^3. A Prescribed Environmental Relevant Activity (ERA) applies to management of the site, and in particular an ERA60(4) related to maintaining a decommissioned landfill is applicable to operation of the site for a period of at least 30 years.

The North Coast Railway Line borders the site to the south and abuts a mangrove forest. Chinaman and Boughtons Creek flow through this mangrove forest on the western and eastern boundary, respectively. Both creeks flow into Smith Creek before reaching Trinity Inlet and the ocean.

This landfill site was active from 1984 to 2009 and was capped in 2011. The capping includes topsoil for vegetation cover (grass) and a engineered lined cap, necessary for landfill gas collection and management. The landfill gas is collected by a gas collection system of vents and pipes and then flared to reduce greenhouse gas emissions associated with the closed landfill. Site runoff and drainage is collected in drains, which discharge into a perimeter drain on the edge of the landfill site. A leachate collection system, including monitoring equipment, sumps, and pumping stations, is operational around the site.

Figure 2-2 shows site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-2 Portsmith Closed Landfill

Several key strategic assets are located on this site, including the material recovery precinct, which is crucial in meeting Councils waste recovery ambition as outlined in the current Cairns Regional Council Waste Strategy which targets a 70% recovery rate by 2027.

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal management district
  - Coastal area – erosion prone area
  - Coastal area – medium storm tide inundation area
  - Coastal area – high storm tide inundation area
- Fish habitat area: Fish habitat management area B
- Water resources: Water resource planning area boundaries
- Native vegetation clearing: Regulated vegetation management map (Category A and B extract)
- State Transport Corridor: Railway corridor
- Area within 25m of a State transport corridor: area within 25m of a railway corridor

187 assets have been identified across this site. These includes a range of infrastructure for capping, monitoring, draining, and resource recovery, including the Portsmith Material Recovery Precinct, Glass Processing Facility, LFG flaring system and Control house.

2.1.2 Yorkeys Knob closed landfill (now Half Moon Bay Golf Club) – Wattle St, Yorkeys Knob

The Yorkeys Knob Landfill site is located at the end of Wattle Street, Lot 233 on SP122860 (Freehold). The site is currently used as a golf course. The site is located along Half Moon Creek over an approximately 300m riverfront.

The landfill is located behind Half Moon Bay Marina and a dune system and therefore is protected from direct wave impact. The landfill is bordered by an approximately 40 m wide strip of vegetation which is Unallocated State Land (50USL9567), which runs along Half Moon Creek, creating a buffer from the creek to the landfill site. The landfill area, estimated to correspond to the elevated area of the Golf Course, is approximately 6.65ha. The parcel has several environmental constraints, such as Fish Habitat Area, Great Barrier Coast Marine Park, MSES etc.

Figure 2-3 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-3 Yorkeys Knob Closed Landfill

Waste disposal on the site started sometime between 1977 and 1983 and ended in 1997. Waste consisted of household waste, general waste and hardfill waste. No liner or leachate system exists. The landfill is surrounded by a perimeter bund constructed to limit tidal ingress and contain the waste.

Landfill closure works were undertaken in 1999 by Council, which included a perimeter stormwater collection drain, capping, gas vents, leachate collection sumps and monitoring wells. The capping comprises a minimum of 250 mm topsoil and 300 mm compacted clay.

The Yorkeys Knob Landfill is classified as "High Environmental Risk" by the EHP landfill monitoring guidelines. A 2012 report (Golder, 2012) found limited leachate impacts in the surface water but identifiable leachate impacts in the groundwater, specifically along the eastern boundary. The site has also been classified as "high potential for methane generation".

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal management district
  - Coastal area – erosion prone area
  - Coastal area – medium storm tide inundation area
  - Coastal area – high storm tide inundation area
- Fish habitat area: Fish habitat management area B
- Water resources: Water resource planning area boundaries
- Native vegetation clearing: Regulated vegetation management map (Category A and B extract)

31 assets have been identified across this site. These include an LFG venting system, perimeter drain, vegetated bund (grass cover) and lawn cap.

2.1.3 Machans Beach closed landfill (now Trinity Barron Sports Club) – Marshall St, Machans Beach

The Machans Beach closed landfill site is located along Marshall Street, Lot 2 RP 721342 (Freehold). The site area is 1.82ha. The site is bordered by residential development and roads to the north and east and a mangrove area to the south and west. The site is approximately 120m away from the ocean with a rock seawall, residential housing and road in between. The site is approximately 150m away from Redden Creek. Redden Creek only occasionally breaches the beach directly south of the site. Redden Creek also drains into the Barron River approximately 3km upstream from the inlet.

Figure 2-4 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-4 Machans Beach Closed Landfill

The site was active from approximately 1965 to 1982, mainly containing household, general, and hardfill waste. No formal liner or leachate collection system is present. The waste volume is estimated to be 50,000 to 100,000m^3.

The site capping was upgraded in 2011 with at least a 0.5m thick, clean soil cap. The mound is shaped to promote stormwater runoff. The site is currently used as a sporting field (recreational space).

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal management district
  - Coastal area – erosion prone area

    - Coastal area – medium storm tide inundation area
    - Coastal area – high storm tide inundation area
- Water resources: Water resource planning area boundaries
- Native vegetation clearing: Regulated vegetation management map (Category A and B extract)

13 assets have been identified across this site. These include four buildings (clubhouse and ancillary buildings), vegetated bunds (shrub cover), sediment and sand pit and lawn cap.

2.1.4 White Rock closed landfill – Sheehy Rd, White Rock

White Rock Landfill is located at the end of Sheehy Road, Lot 27 SP 109010 (Reserve). The site area is 5.87ha. The site is bordered by residential development to the west and a mangrove area to the north, east and south. Crowleys Creek flows along the eastern boundary and Sawpit Gully flows to the south of the site. Both drain into Skeleton Creek, Smith Creek and then Trinity Inlet. The site is approx. 10km upstream from the ocean. Figure 2-5 shows the extent of the site.

Figure 2-5 White Rock Closed Landfill

The site was cleared around 1977 and was active until 1998. Waste included mainly household waste, general waste and hardfill deposited on site. The waste area is enclosed in a perimeter bund to contain the waste and limit tidal ingress. The area within this perimeter bund would correspond to the landfill area and is approximately 5.3ha.

Landfill closure was undertaken in 1999. Capping consists of interim soil cover, GCL and a minimum 250mm topsoil. Closure works also included the installation of a perimeter stormwater collection drain, leachate collection sumps and leachate monitoring wells, and gas vents. No formal liner or leachate collection system appears to be present.

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal management district
  - Coastal area – erosion prone area
  - Coastal area – medium storm tide inundation area
  - Coastal area – high storm tide inundation area
- Fish habitat area: Fish habitat management area B
- Native vegetation clearing: Regulated vegetation management map (Category A and B extract)

50 assets have been identified across this site. These include perimeter access road, stormwater perimeter drains and spillways, LFG vents, perimeter pumping and leachate collection infrastructure, armoured rock bunds (stone and stone pitching works), monitoring stations, grass caps.

2.1.5 Endeavour Park sporting fields – Cannon St, Manunda

The Endeavour Park closed landfill is located on Lot 124 SP 227603 (hazardous landfill) and Lot 21 to 26 C19842 (Reserve) and is currently known as Endeavour Park, on Cannon Street. The sporting fields cover an area of approximately 11.2 hectares. Endeavour Park is listed on the Queensland Environmental Management Register (EMR) but does not have an approved Site Management Plan (SMP) to guide ground disturbance activities.

The site is approx. 3.5km upstream from the ocean and is bordered by residential development to the east and south and a mangrove area to the west. An open drain runs along the northern boundary, which drains into Lily Creek. Lily Creek drains directly into the ocean south of the airport. Figure 2-6 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-6 Endeavor Park Closed Landfill

Council indicated that the landfill was active between 1950 and 1967. The site has been closed for approximately 56 years, with an estimated 2m to 3m landfill depth. The site was predominantly used to dispose of household waste, including plastic, cloth, glass and metal waste. The waste also contains asbestos-containing material (ACM). Benzene hexachloride (BHC) traces have also been found in the landfill but not in the cap. This suggests that the site contains a mixture of household waste, general waste and hardfill waste.

Cairns Regional Council Report (2007) noted that an irrigation bore was in use on the site at a depth of 60-80 feet, and water testing showed no indication of any leachate impacts on groundwater from the landfill site.

Golder (2006) reports that the topsoil layer cap is typically between 0.25m and 0.5 m thick and is considered free of contaminants. For an old landfill, capping is necessary to maintain a physical barrier between refuse and site users. However, capping is less critical for trapping gases and leachates than on a new landfill site. The top layer was disturbed during works for the Endeavour Park Upgrade in 2013, but it is assumed in this study that at least a 0.25m cap has been maintained in situ.

The WSP Asbestos in Soils Management Plan (2022) details further that Council classified the blue area in Figure 2-6 as a “hazardous landfill” (car park area) while the remaining site (sports field) is a “Former Landfill”.

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal area – erosion prone area
  - Coastal area – high storm tide inundation area

22 assets have been identified across this site. These includes stadium infrastructure such as buildings, stands, car parks and pitches as lawn cover.

2.1.6 Aeroglen Sporting fields – Aeroglen Drive, Aeroglen

The Aeroglen Sporting Field closed landfill is located on Reserve Lot 496 C198327 (Reserve) and is currently known as Aeroglen Sporting Fields, along Aeroglen Drive. The site is approximately 8.5 hectares. A proportion of this site, approximately 6.21 hectares, is covered by lawns, which are assumed to be the extent of the landfill site. The site was still in use in 1991 as burning is visible on State aerial picture archives on the southern portion. The remaining area is a pathway, creek, mangrove and forest at the base of the Mount Whitfield Conservation Park. The site drains into Saltwater Creek towards the south.

GHD (2006) reports that the topsoil layer is variable, with depths of 0.1-1.5m. The top soil layer is typically underlain by household landfill debris, including plastic, cloth, glass and metal, to at least 3.0 meters (according to leachate bore data). A further report from Golders indicated, "providing the soil cover is maintained over the landfill materials, there is no pathway for site users to be exposed to asbestos or asbestos materials. Therefore, a health risk does not exist at the locations investigated.”

Figure 2-7 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-7 Aeroglen Sporting Field Closed Landfill

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal area – erosion prone area
  - Coastal area – medium storm tide inundation area
  - Coastal area – high storm tide inundation area
- Water resources: Water resource planning area boundaries
- Native vegetation clearing: Regulated vegetation management map (Category A and B extract)
- State Transport Corridor: State-controlled road
- Area within 25m of a State transport corridor: area within 25m of a state-controlled road

28 assets have been identified across this site. These include stormwater drainage, car parks, toilet blocks and lawn cover.

2.1.7 Mann St Sporting Fields – Mann St, Westcourt

The Mann Street Sporting Field closed landfill is located on Lot 2 SP182733 (Freehold) and Lot 3 NR7338 (Lands Lease). The site area, including the Jones Park sporting complex, is 8.914 hectares. Most of the site is covered by lawns, which is assumed to be the extent of the landfill site. The true extent of the landfill is unknown, although the State aerial pictures collection shows that the site was actively developed from the 1950s to the early 1980s, when the southern section of Lot 2 was developed into two sports fields. The field area drains towards Lot 3 and then into Smith Creek drain. Figure 2-8 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-8 Mann Street Sporting Field Closed Landfill

No information was provided on the nature of the containment works and cap.

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal area – erosion prone area
  - Coastal area – high storm tide inundation area
- Native vegetation clearing: Regulated vegetation management map (Category A and B extract) (Lot 2 only)

43 assets have been identified across this site. These includes stadium infrastructure such as buildings, stands, car parks and lawn cover.

2.1.8 Barlow Park Sporting fields – Scott St, Bungalow

The Barlow Park Sporting Field closed landfill is located on the southern section of Lot 761 SP338643 and 766 Lot SP338643. The northern section of this allotment is the location of the Cairns Showground. This site is adjacent to the Jones Park sporting complex and is approximately 81.2 hectares in area. A stadium has been developed on the site. The true extent of the landfill is unknown, although the State aerial pictures collection shows that the site was constructed in the late 1960s, when the Smith Creek drain was built, and the wetland south of the Cairns Showground was reclaimed.

Landfill waste materials have been found in the south-east corner of Smith Creek and Scott Street, along the Barlow Park Sporting Complex car park. Previous reports from Douglas Partners (2016) and Golder Associates (2016) related to the investigation of lighting upgrade at Barlow Park concluded that “these waste materials fall under the definition of “general waste” under the Environment Protection (Waste Management) Regulation 2000, does not constitute a regulated waste and therefore not a trackable waste”. Further soil testing in 2018 found traces of heavy metals. It appears plausible that most waste on this site may not be household waste but is related to past developments on and neighbouring the site.

Figure 2-10 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-9 Barlow Park Sporting Field Closed Landfill

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal area – erosion prone area
  - Coastal area – medium storm tide inundation area
  - Coastal area – high storm tide inundation area
- State Transport Corridor: State-controlled road
- Area within 25m of a State transport corridor: area within 25m of a state-controlled road

35 assets have been identified across this site. These include stormwater drains, shared paths, stadium infrastructure, buildings, stands, car parks and lawn cover.

2.1.9 Cairns Esplanade Foreshore Park

The Cairns Esplanade closed landfill site is located on Lot 711 SP315908 (Reserve) and is 12.3ha in area. Several redevelopment works have occurred on the Esplanade since the late 19th century. Landfill reclamation works occurred in the early 1980s along the Esplanade from the Hospital and towards the north of the site.

Various degrees of contamination have been found and reported in the 21st century, including – but not limited to – asbestos products, rubble, and other demolition waste related to nearby demolition works. Remediation works have included lining and waste relocation. It appears plausible that most waste on this site may not be household waste but is related to the past developments on and neighbouring the site.

The site is typically elevated and forms an informal coastal levee along the Cairns foreshore. The site forms a buffer zone between the built environment and the beach. The landfill area would be limited to the area outside the beach, approximately 11.0ha. A network of stormwater drains is located inland along the Cairns Esplanade roadway. A seawall of various forms and conditions has been built along the shoreline. Waste was identified on the Esplanade beach, such as bricks and asbestos fragments, during our site visit in December 2022.

Figure 2-10 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-10 Cairns Esplanade Closed Landfill

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal management district
  - Coastal area – erosion prone area
  - Coastal area – medium storm tide inundation area
  - Coastal area – high storm tide inundation area

  The site is neighbouring Trinity Inlet, a Fish Habitat Area A and B.

37 assets have been identified across this site. These includes stormwater drains, shared paths, car parks, lookout, seawall, sports ground, BBQ, various amenities and lawn cover.

2.1.10 Holloways Beach

The Holloways Beach site is located on Lot 235 NR5479 (reserve), approximately 1.54ha. It is hypothesised that other similar sites may exist along the coast, particularly in mangrove areas, as informal landfill development is typically associated with early settlement phases.

While the past development of this site is unknown, the State aerial photograph shows that there was no activity at this site circa 1952, with bush covering the area. An access track was built by 1965, which connects Ritcher Creek to the coastal road developed along Holloways Beach. The hypothetical landfill is covered by a blue gravel cap spread south of the boat ramp on Acacia Street Park. The corresponding estimated landfill area is approximately 0.65ha. Saltbush and lawn cover is growing intermixed in the gravel cap.

Figure 2-11 shows the site cadastral boundaries extracted from the Queensland Globe database.

Figure 2-11 Holloway Beach Closed Landfill

The Queensland Development Assessment Mapping System lists the following Matters of Interest for this site:

- Coastal protection:
  - Coastal management district
  - Coastal area – erosion prone area
  - Coastal area – high storm tide inundation area
- Water resources: Water resource planning area boundaries
- Wetland Protection Area: Wetland protection area trigger area
- Native vegetation clearing: Regulated vegetation management map (Category A and B extract)

Only one asset, the gravel landfill cap, has been identified at this site. The Public boat ramp is located north of this hypothetical coastal landfill site.

2.2 Planning matters

The Environmental Protection Act (1994) establishes a General Environmental Duty (GED) mandating that no one should engage in activities that could lead to environmental harm unless they take reasonable and practical steps to prevent or minimize such harm (i.e., duty of care).

The GED extends its reach to anyone involved in activities within Queensland or elsewhere that could impact Queensland's environment. This duty of care extends to land occupiers, including tenants of community facilities located on closed landfill sites.

Two important public registers in Queensland, the Environmental Management Register (EMR) and the Contaminated Land Register (CLR), contain essential information about contaminated land. This includes permit conditions and other necessary operational requirements.

Closed landfill sites demand a higher level of pre-planning, site assessment, and effective management of contaminated soil if one intends to excavate or carry out development work.

Land is included in the EMR if specific activities, known as notifiable activities, have taken place or are ongoing on that land or if the land is known to be contaminated. Contaminated land, in this context, refers to land affected by hazardous contaminants.

The Environmental Authority, with the identifier EPPR00887713, specifies Environmentally Relevant Activities (ERA) and their locations within the Cairns Regional Council area. Only the Portsmith Landfill Recovery Way, located at Portsmith Qld 4870 Lot 17 on Plan SP270880, holds an ERA 60(4) permit for "Maintaining a decommissioned landfill." Procedures are in place to manage environmental hazards at the White Rock and Yorkeys Knob Close Landfills.

A Contaminated Land Management Plan (CLMP) can be developed to plan and execute projects on closed landfill sites. Such a plan would include preliminary technical investigations and inputs from experts in assessing and managing contaminated sites. Future work at closed landfill sites requires a CLMP.

The Cairns Waste Reduction and Recycling Strategy demonstrates that landfill volume per capita has been reducing as waste management practices have evolved. The management of closed landfill sites remains an ongoing concern for the Council.

2.3 Summary

Approximately 2.8 million m^3 of landfill waste and 447 assets were identified on Council's closed landfill sites. Figure 2-12 shows the typical configuration of a closed landfill site.

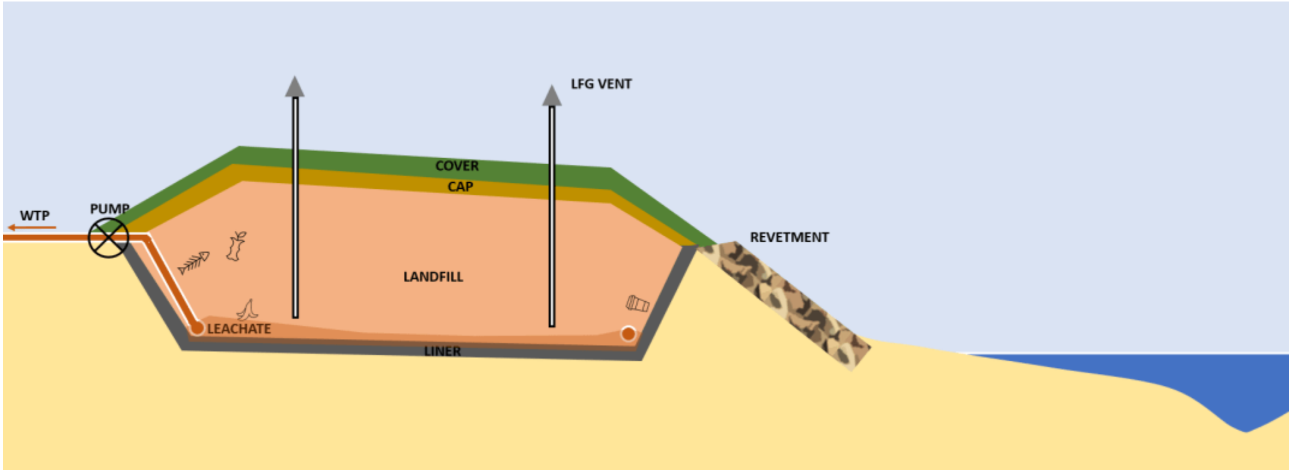

Figure 2-12 Landfill site typical configuration

Table 2-1 compares the 10 sites.

Table 2-1 Cairns Coastal Closed Landfill Site Summary

Site ID	Location	Receiving environment	Fish Habitat Area	Date			Cap Type, thickness (mm)	Bund Type	Substrate	Liner	Waste Type	Landfill Area (m²)	Landfill Volume - Method of measurement	Assets	Estimated Landfill Volume (m³)
				Opened	Closed	Capped									
1	Portsmith	Chinaman and Boughtons creeks	A, B	1984	2009	2011	Topsoil and CCL	Riprap – Boughtons creek	Soft soil	Yes, GCL	household waste, general waste and hardfill waste	215,134	Council estimate	187	1,700,000
2	Yorkeys Knob	Half Moon Creek	B	1977	1997	1999	300 CCL + topsoil	Grass, Mangrove	Sand	No	household waste, general waste and hardfill waste	66,500	Council estimate	31	160,000.
3	Machans Beach	Redden Creek - ICOLL or Barron River	N/A	1965	1982	2011	500 clean soil	Shrubs and trees	Soft soil	No	household waste, general waste and hardfill waste	18,160	Council estimate	13	100,000
4	White Rock	Crowley Creek, Sawpit Gully	B	1977	1998	1999	300 CCL+ 250 topsoil min, GCL	Riprap	Soft soil	Yes, likely clay	household waste, general waste and hardfill waste	53,000	Council estimate	50	250,000
5	Endeavour Park	Lily Creek	N/A	1950	1967	1967	250 topsoil min	Riprap - Lily creek	Reclaim	No	household waste, general waste and hardfill waste	112,750	assume averaged 2m depth	22	225,000
6	Aeroglen	Saltwater Creek	N/A	1950	1993	1993	100 topsoil min.	None	Soft soil	No	household waste, general waste and hardfill waste	62,100	assume averaged 1m depth	28	62,000
7	Mann St	Smith Creek	N/A	1950	1980	1983	100 topsoil min.	Riprap – Smith Creek	Reclaim	No	household waste, general waste and hardfill waste	89,140	assume averaged 2m depth	43	180,000
8	Barlow Park	Smith Creek	N/A	1960	1980	1976	100 topsoil min.	Riprap – Smith Creek	Reclaim	No	general waste and hardfill waste	81,200	Assumption	36	10,000
9	Cairns Esplanade	Trinity Inlet	A, B	1983	1990	1983	100 topsoil min.	Seawall of various conditions	Soft soil	No	general waste and hardfill waste	110,300	Assumption	37	10,000
10	Holloways Beach	Richters Creek	N/A	1965	1982	1982	50 gravel	Mangrove	Soft soil	No	household waste, general waste and hardfill waste	6,500	Assumption	1	2,000

3 COASTAL HAZARDS

The coastal landfill sites and assets are vulnerable to several coastal hazards, including:

- Permanent coastal inundation due to sea level rise;
- Episodic coastal flooding due to storm tides and wave actions during tropical storms and cyclones;
- Erosion of landfill site perimeter bunds; and
- Scour of landfill cap and damages due to submergence, such as potholes and cracks developing following flooding.

3.1 Rainfall run-off

The climate at Cairns is tropical, with high rainfalls and temperatures. The Bureau of Meteorology (BOM) has collected continuous rainfall observations for Cairns Airport since September 1942. Table 3-1 shows a monthly summary of statistics for all years.

Table 3-1 Monthly Rainfall, Cairns Airport

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	402.2	437.1	414.7	201.7	91.7	46.3	33.2	26.2	32.8	47.7	89.7	182.2	1,999.6
Lowest	86.1	30.4	27.8	13.0	3.2	3.2	-	-	-	-	-	9.0	721.0
5th %ile	112.8	108.2	102.0	26.5	15.6	4.4	3.8	1.4	0.8	2.3	7.6	33.9	1,216.4
10th %ile	121.0	136.0	134.4	56.1	27.4	9.0	7.4	3.3	2.3	5.4	17.6	42.6	1,376.8
Median	353.3	395.8	374.2	163.2	84.8	35.0	26.8	17.0	18.6	29.4	62.8	124.8	1,975.6
90th %ile	651.8	741.0	771.6	398.8	176.3	91.9	59.8	62.6	83.9	94.6	204.4	357.8	2,780.5
95th %ile	825.2	864.0	906.6	472.0	191.8	115.8	89.4	72.2	88.6	158.8	275.8	581.9	2,836.6
Highest	1,417.4	1,287.0	1,127.5	845.2	322.3	177.6	145.0	140.2	103.2	394.4	372.0	919.4	3,148.8

Median annual rainfall is approximately 2.0m and is influenced by tropical cyclone season rainfalls from November to April. Cyclones within the Coral Sea and sometimes in the Gulf of Carpentaria affect the region regularly. On average, since 1959, 1.38 tropical cyclones per year have entered the Cairns region. This includes Tropical Cyclone Yasi of 2011, which crossed the coast 140km south of Cairns. The last major cyclone directly affecting Cairns occurred in March 1934, resulting in widespread damage and loss of life.

The BOM provides Intensity Frequency Duration (IFD) data from Australian Rainfall and Run-off guidelines (ARR, 2016). IFDs are designed rainfall depths (mm) corresponding to selected standard probabilities based on the statistical analysis of historical rainfall. Figure 3-1 shows the rainfall total for several Annual Exceedance Probability (AEP).

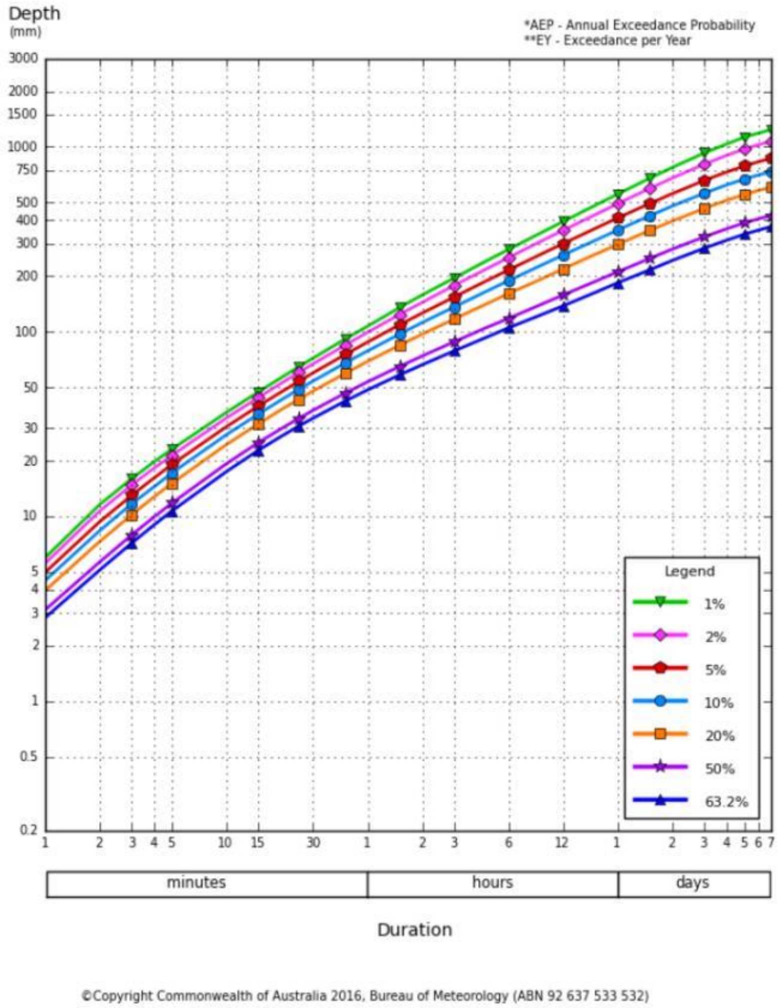

Figure 3-1 Cairns IFD, ARR 2016

Such high rainfall intensity is challenging for stormwater management and erosion management of landfill caps.

3.2 Tides

Astronomical tides are the ‘normal’ rising and falling of the ocean in response to the gravitational influences of the moon, sun, and other astronomical bodies. These effects are predictable; consequently, astronomical tide levels can be forecast with high confidence.

In a lunar month, the highest tides occur at the time of the new moon and the full moon (when the gravitational forces of the sun and the moon are aligned). These are called **spring** tides and occur every 14 days. Conversely, **neap** tides occur when the gravitational influences of the sun and moon are not aligned, resulting in high and low tides that are not as extreme as those during spring tides.

Tidal planes at the Cairns Port are semi-diurnal (twice daily). Marine Safety Queensland (MSQ) tidal planes, extracted from the Queensland Tide Tables (QTT) 2023, are reproduced in Table 3-2.

Table 3-2 Cairns Tidal Planes, 2023

Tidal Plane	Level (m LAT)
Lowest Astronomical Tide	0.00
Mean Low Water Spring MLWS	0.88
Mean Low Water Neap MLWN	1.55
Australian Height Datum AHD	1.645
Mean Sea Level MSL	1.79
Mean High Water Neap MHWN	2.04
Mean High Water Spring MHWS	2.71
Highest Astronomical Tide	3.58

The level of AHD at PSM96052, located on Cairns Wharf No 2 was surveyed at 3.363m AHD on 16 March 1992. This Permanent Survey Mark (PSM) had a Reference Level of 5.008m LAT in the 2023 QTT. This suggests a net sea level rise of 0.145m, or a rate 4.7mm per year over the period 1992 to 2023.

Spring tides tend to be higher than usual around the Christmas/New Year period (i.e., December - February) and mid-year (i.e., around May - July) during the equinox. The various occurrences of exceptionally high spring tides are often referred to in lay terms as 'king tides' - in popular terminology, meaning any high tide well above average height.

Tidal predictions are computed based on astronomical influences only, without considering meteorological effects that influence ocean water levels. When meteorological conditions change significantly from the average, they can cause significant differences between predicted tides and actual sea level observations. Deviations from predicted astronomical tidal heights are often caused by strong or prolonged winds and/or by uncharacteristically high or low barometric pressures.

3.3 Climate Change

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) of 2007 provided a range of global sea level rise projections. The Queensland Department of Environment and Science reviewed the AR4 report and adopted a sea level rise projection of +0.8 m above present-day levels by 2100 for coastal management purposes in Queensland. The Queensland Coastal Hazard Technical Guide (Department of Environment and Heritage Protection, 2013) notes that this sea level rise allowance is similar to the recommendation of the fifth Assessment Report (AR5) of 2014.

This 0.8m Sea Level Rise projection is consistent with the RCP 8.5 global Representative Concentration Pathway (RCP) RCP8.5 emission scenario. This study has applied such considerations, which are aligned with the CHAS. The Storm Tide inundation mapping included the following amount of sea level rise adopted for this project.

Table 3-3 Sea Level Rise Allowance

Year	2020	2040	S2060	2080	2100
Sea Level Rise Allowance, m	0	0.1	0.25	0.45	0.80

Research into the implications of sea level rise for Australia is routinely conducted by a broad spectrum of individuals and organisations, including universities, research institutes, consultancies, government bodies and community groups.

The IPCC Sixth Assessment Report indicates that thermal expansion of the oceans and glacial melting have been the dominant contributors to 20th century global mean sea level rise, and this pattern is likely to continue to 2100.

The report states, "*Global mean sea level increased by 0.20 m between 1901 and 2018. The average rate of sea level rise was 1.3 mm/yr between 1901 and 1971, increasing to 1.9 mm/yr between 1971 and 2006, and further increasing to 3.7 mm/y between 2006 and 2018 (high confidence). Human influence was very likely the main driver of these increases since at least 197*1".

This may be compared with the 4.7mm/year over 1992 to 2023 estimated from the AHD survey data and tidal projections provided by MSQ.

The dominant cause of Global Mean Sea Level Rise since 1970 is the anthropogenic (human-induced) release of Greenhouse Gas (GHG) emissions. The recently published IPCC 6th Assessment Report (AR6) opens with a clear statement *"It is unequivocal that human influence has warmed the atmosphere, ocean, and land. Widespread and rapid changes in the atmosphere, ocean cryosphere and biosphere have occurred"* (IPCC, 2021).

The AR6 updates sea level rise projections and provides local sea level rise information about sea level rise in Cairns, corrected to include Total Sea Level accounting for local vertical land movements, stereo-dynamic and glacier ice loss effects.

The speed of future sea level rise remains somewhat uncertain, mainly because future anthropogenic GHG emissions remain uncertain. The future release of greenhouse gases significantly affects the timing of future sea levels. Therefore, the assessment focused on possible future GHG emissions scenarios.

As part of the AR6, SLR projections have been provided for five (5) future scenarios – referred to as Shared Socio-economic Pathways (SSPs) – that, in broad terms, refer to the following global GHG emissions scenarios:

- **SSP1-1.9:** Very low GHG emissions: CO_2 emissions cut to net zero around 2050.
- **SSP1-2.6:** Low GHG emissions: CO_2 emissions cut to net zero around 2075.
- **SSP2-4.5:** Intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100
- **SSP3-7.0:** High GHG emissions: CO_2 emissions doubled by 2100.
- **SSP5-8.5:** Very high GHG emissions: CO_2 emissions tripled by 2075. This scenario trends along GHG emission over the last 10 years

Figure 3-2 shows the SSP scenarios and uncertainties in Sea Level Rise for Cairns, relative to a 1995-2014 baseline. Shaded areas represent projection uncertainties to show the 17th-83rd percentile.

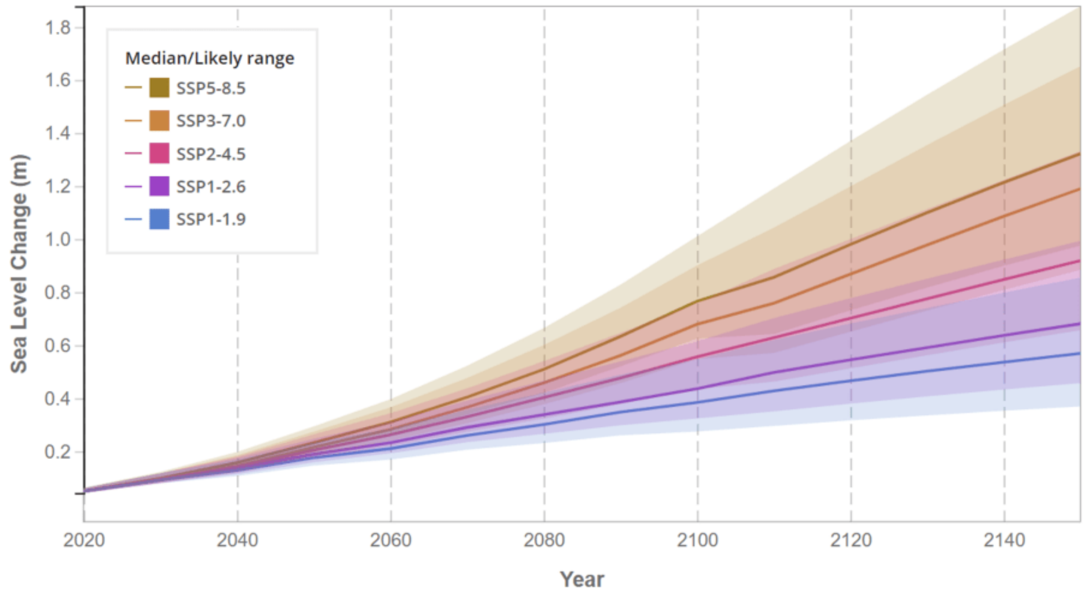

Figure 3-2 Cairns Sea Level Rise Projects, AR6

The AR6 likely range for 2100 (17%-83% confidence interval) is 0.62-1.01m with a median projection at 0.77m. While the median projection remains very close to the DES Policy, a risk-based assessment would factor in the complexity of a project in establishing a suitable sea level rise allowance.

Figure 3-3 shows the projected timing of Total Sea Level Rise reaching 0.8m under different SSPs. Thick bars show 17th-83rd percentile ranges, and black circles show median values. Thin bars also show 5th–95th percentile ranges for SSP1-2.6 Low Confidence and SSP5-8.5 Low Confidence scenarios. This diagram indicates that the Total Sea Level Rise at Cairns reach 0.8m sometime after 2070, irrespective of SSP.

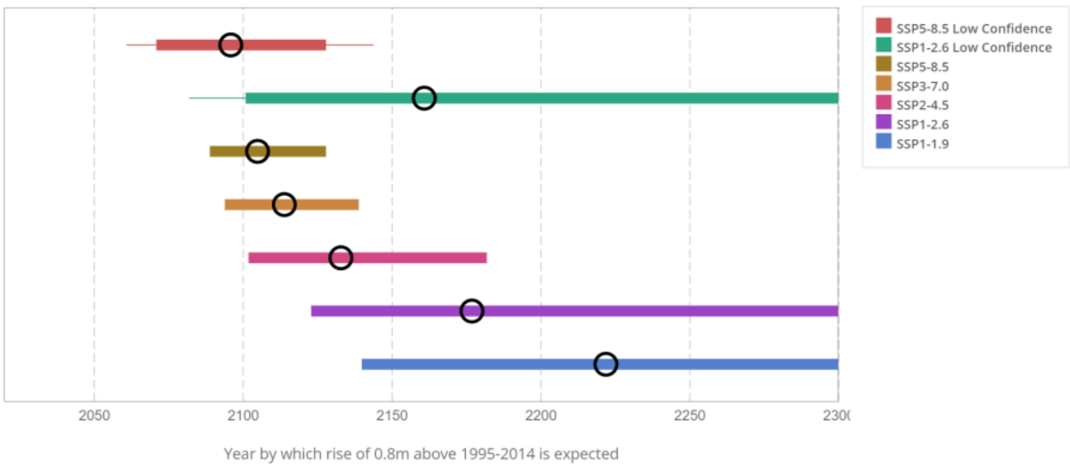

Figure 3-3 Cairns timeline for 0.8m Sea Level Rise, AR6

The key points to note about the sea level rise projections update are as follow:

- The rate of mean sea level rise is projected to increase throughout the 21st Century;
- The Queensland planning benchmark for sea level rise of 0.8m by 2100 is consistent with the latest findings of the AR6 IPCC, indicating that this level is going to be reached at some point in the next 100 years, unless a very substantial and permanent reduction is GHG emissions occurs in the next decades;

- Mean Sea level will continue to rise beyond 2100 and eventually reach 0.8m, irrespective of GHG emissions;
- Because of the continued sea level rise over the next centuries, it would be prudent to consider higher sea level rise for planning significant infrastructure developments along the coast; and
- A risk-based approach may be warranted for planning key coastal infrastructure in the long term. This implies that critical infrastructure should consider more conservative climate change allowances than standard infrastructure.

The Ethos Urban - BMT WBM 2019 Cairns Coastal Hazard Adaptation Study modelled sea level rise inundation for the five sea level rise allowances listed in Table 3-3.

3.4 Storm Tides

The astronomical tide dominates coastal water levels in the study area. However, variations from the predicted tide level can occur due to meteorological events, particularly during storms when high wind and low atmospheric pressure contribute to increased sea levels. These variations are referred to as storm surges. The storm tide is the total water level resulting from predicted astronomical tides plus the increase in the storm surge.

Figure 3-4 illustrates the components of a storm tide event, including the nearshore wave processes contributing to coastal flooding.

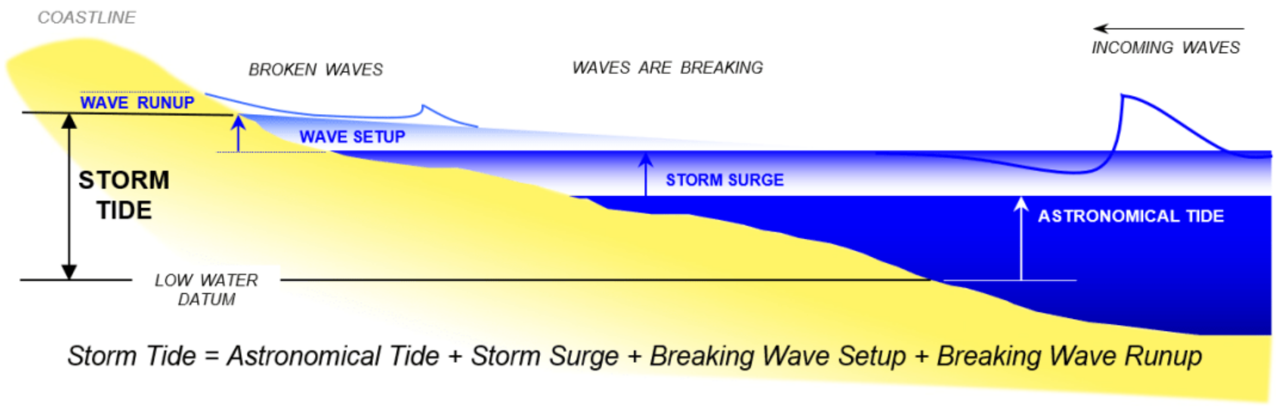

Figure 3-4 Storm Tide Components

The storm tide assessment undertaken by the Ethos Urban - BMT WBM 2019 Cairns Coastal Hazard Adaptation Study (CHAS) was used for the coastal landfill study. The BMT Study was a remodelling of work that BMT WBM did for Council under the 'Cairns Region Storm Tide Inundation Study' January 2013, and another output is the BMT WBM 'Coastal Erosion Prone Areas' modelling 2019.

The BMT model included the following effects in storm tide modelling to account for tropical cyclone changes:

- Sea level rise of 0.8m by the year 2100;
- A 10% increase in the maximum cyclone intensity; and
- A 1.1m sea level rise was also modelled on request from Cairns Regional Council.

The Ethos Urban - BMT WBM 2019 Cairns Coastal Hazard Adaptation Study modelled the storm tide flooding for a 100-year Average Recurrence Interval storm tide for various sea level rise allowances listed in Table 3-3.

All outputs from the CHAS Study were remodelled from the work that BMT WBM did for Council under the ‘Cairns Region Storm Tide Inundation Study’ of January 2013.

3.5 Waves

The Cairns Shoreline Erosion Management Plan (SEMP) prepared by BMT in 2020 provides an update on coastal wave processes in the Cairns Region to the Beach Protection Authority Cairns Beaches Report of 1986.

All sites are sufficiently far from the coast to be effectively excluded from day-to-day coastal processes.

Ambient waves significant height (Hs) is typically up to 1.4m in the offshore waters, which are unlikely to affect the closed landfill sites considered in this assessment significantly. Only the Cairns Esplanade closed landfill site is subject to such direct wave actions; all other sites are protected by mangroves or coastal vegetation.

The Cairns Esplanade seawall and beach system appears reasonably competent to manage erosion and flooding actions related to such ambient waves, but the ability of the seawall to manage run-up, overtopping flow and storm tide during tropical cyclones is reduced. The seawall is also of varying condition and form and may not be to a sufficient engineering standard to mitigate the effect of coastal erosion for a 100-year ARI storm, particularly in the future.

Extreme waves occurring during cyclonic conditions could reach the toe of some of the closed landfill sites located in estuaries. Even though most landfill sites are protected by natural vegetation, such as mangroves, it is plausible that climate change and permanent inundation could affect vegetation over time. Mangroves can only grow and live in intertidal areas: as the sea level rises, the mangrove buffer in front of the landfill sites will narrow and become less efficient at wave attenuation. Therefore, this landfill risk assessment considered that waves could be depth-limited along the edge of the closed landfill sites. While this is a conservative assumption, it provides a level of safety warranted for a regional study.

4 RISK ASSESSMENT

4.1 Risk identification process

The coastal hazards related to the Closed Landfill Sites are as follow:

- **Coastal inundation** – Permanent coastal inundation due to tidal incursion of seawater on land combined with on-going of sea level rise. Coastal inundation would lead to ongoing leachate seepage to the receiving waterways, the release of landfill gas and damage to the landfill bund and capping due to coastal erosion and cap scour. Infrastructure at risk of submergence may also be damaged during a flood event, including leachate pumping, Landfill Gas (LFG) venting and SCADA monitoring systems.
- **Coastal flooding** – Episodic coastal flooding due to storm tide events. Coastal flooding would lead to temporary seepage of leachate to the receiving waterways, the release of landfill gas and damage to the landfill bund and capping due to coastal erosion and cap scour. Infrastructure at risk of submergence may also be damaged during a flood event, including leachate pumping, Landfill Gas (LFG) venting and SCADA monitoring systems.
- **Coastal erosion** - Bund erosion around the closed landfill site due to hydraulic actions such as wave breaking or currents developing on the edges of the landfill. This may result in waste being extracted from the landfill and contaminating receiving waterways.
- **Landfill cap scour** – Scour of the closed landfill cap as well as potholes and cracks, which may develop due to submergence of the landfill site. Landfill caps may not be sufficiently armoured to prevent such abrasion and degradation. This may result in waste being extracted from the landfill and contaminating the receiving waterways.

A first-pass risk analysis has been carried out via mapping to consider coastal inundation and flooding as well as the potential for erosion of the closed landfill sites perimeter bunds and scour of the cap. The analysis has been developed for five planning horizons, including 2020 (present-day), 2040, 2060, 2080 and 2100.

4.2 Risk category

Sea level rise inundation and storm tide flooding area extents were mapped and intersected with assets located on the landfill sites. In total, 448 assets were considered across all the sites. A risk category was assigned for each asset.

The risk categories were based upon the defined hazard vulnerability curves provided in Handbook 7, “Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia” (AIDR 2017), as shown in Figure 4-1.

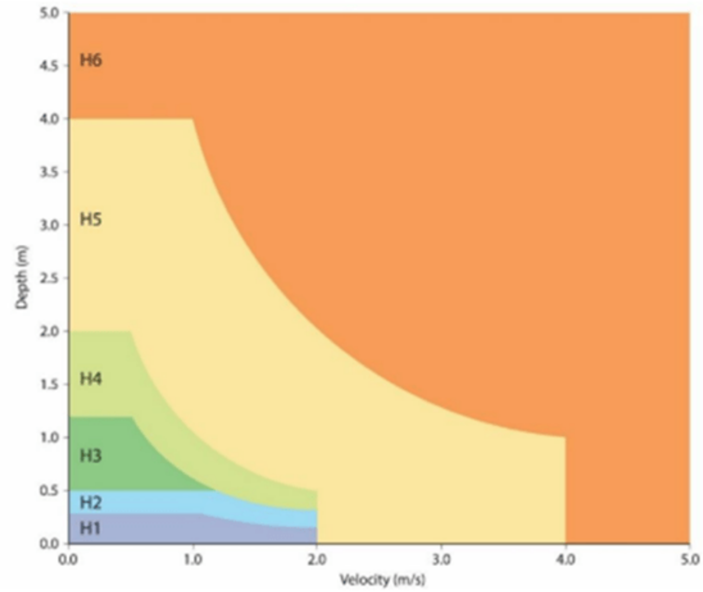

Figure 4-1 Hazard Categories (Source: Handbook 7 AIDR 2017)

CRC has completed a Coastal Hazard Adaptation Study (CHAS) using the QCoast 2100 Minimum Standards and Guidelines. The CHAS assigned broader risk categories and discussion on tolerability to inform the development of planning instrument responses to coastal risk for all assets. This was used as a starting point for the coastal inundation risk assessment.

The 100-year ARI hazard exposure was mapped across the landfill sites for all planning horizons, considering submergence depth and critical flow velocity as indicators of hazard within the storm tide inundation, plus wave effects to map the coastal inundation risk. The use of critical flow velocity in the assessment rules out the possibility of Hazard Category H3.

4.3 Coastal inundation

The coastal inundation assessment for each site is provided in Appendix B. Table 4-1 summarises the results in terms of surface area impacted by permanent inundation over the five planning horizons for each closed landfill site.

Table 4-1 Property coastal inundation summary, m^2

	Landfill area	2020	2040	2060	2080	2100
Portsmith	215,134	3,434	4,194	7,680	11,766	19,753
Yorkeys Knob	66,500		131	361	890	2,398
Machans	18,160		74	318	520	1,024
White Rock	53,000		9	52	172	270
Endeavour	112,750		541	2,330	13,601	46,694
Aeroglen	62,100		385	1,427	2,268	3,582
Mann Street	89,140			48,386	58,838	70,311
Barlow Park	81,200			14,021	32,849	48,607
Esplanade	110,300		34	247	4,195	23,800

	Landfill area	2020	2040	2060	2080	2100
Holloways	6,500	24	2,656	4,542	5,652	6,170

The Yorkeys Knob, Machans, White Rock and Aeroglen closed landfill sites are more resilient to coastal inundation than Mann Street, Barlow Park, the Esplanade or Holloways. Portsmith is quite vulnerable as the perimeter road and sediment basin become submerged permanently over time. Table 2-1 indicates that the landfill volume for Barlow Park, Esplanade and Holloways may be relatively small. Therefore, Endeavour Park, Mann Street and Barlow Park appear to be the more challenging sites from a coastal inundation management perspective.

From an asset perspective, Table 4-2 summarises the number of assets at coastal inundation risk across all the sites for each hazard category and each planning horizon.

Table 4-2 Asset Hazard category – Coastal Inundation – All Sites (448 samples)

HC	2020	2040	2060	2080	2100
H1	6	12	30	29	37
H2	13	4	21	18	14
H3	0	0	0	0	0
H4	1	9	17	14	8
H5	27	24	38	67	99
H6	9	15	29	35	45

For further details, Figure C-12 details each site's hazard category and planning horizon considered in this study. Figure 4-2 stacks the number of assets inundated over time and in each hazard category.

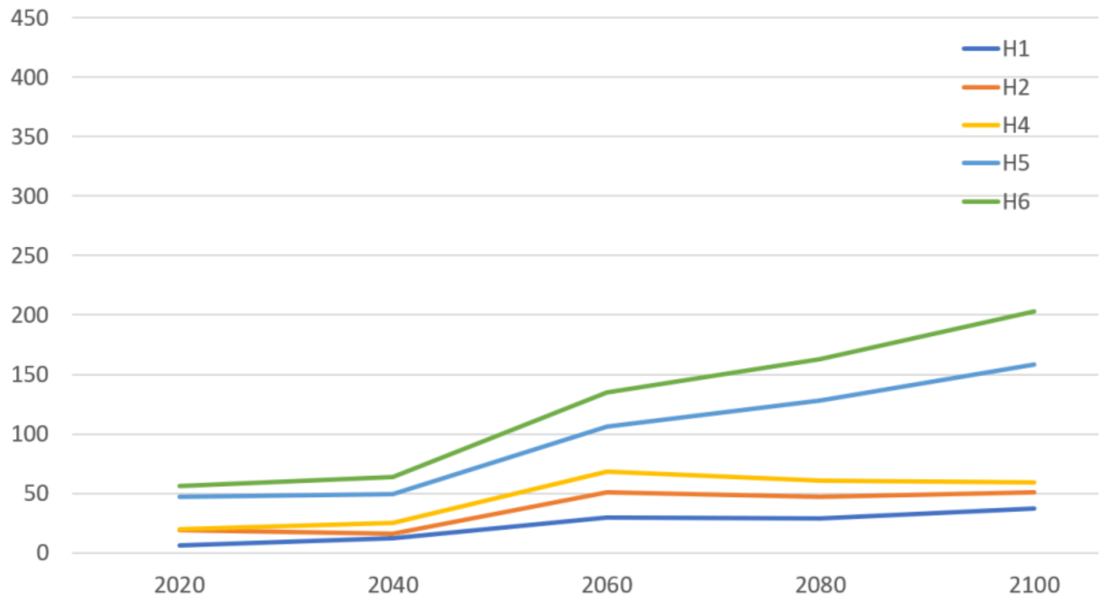

Figure 4-2 Asset inundation vulnerability

As sea level rises, more and more assets become vulnerable to coastal inundation. Appendix D shows how individual assets are affected by coastal inundation over time for a representative number of assets around the closed landfill sites.

4.4 Coastal flooding

Coastal flooding mapping corresponding to a 100-year ARI storm tide for each site is provided in Appendix C. Table 4-3 summarises the results in terms of surface area impacted by occasional tropical cyclone flooding over the five planning horizons for each closed landfill site.

Table 4-3 Property coastal flooding summary, m²

	Landfill area	2020	2040	2060	2080	2100
Portsmith	215,134	10,896	13,203	19,537	25,908	33,314
Yorkeys Knob	66,500	104	211	509	1,040	2,960
Machans	18,160	495	592	1,091	1,431	2,701
White Rock	53,000	244	290	333	593	1,107
Endeavour	112,750	4,611	10,389	26,715	65,829	112,771
Aeroglen	62,100	1,312	1,768	2,715	3,642	13,391
Mann Street	89,140	54,043	59,040	67,132	73,945	85,923
Barlow Park	81,200	22,886	34,004	44,122	57,555	73,229
Esplanade	110,300	78,565	86,752	99,623	107,357	109,758
Holloways	6,500	2,842	4,153	5,454	5,996	6,412

The Yorkeys Knob, Machans and White Rock closed landfill sites are more resilient to coastal flooding than Mann Street, Barlow Park, the Esplanade or Holloways. Portsmith transfer station buildings are somewhat vulnerable to coastal flooding, noting that there is a high likelihood of a flooding risk beyond the 100-year-ARI storm tide for several key buildings because the site is low-lying. Table 2-1 indicates that the landfill volume for Barlow Park, Esplanade and Holloways may be relatively small. Therefore, Endeavour Park, Mann Street and Barlow Park appear to be the more challenging sites from a coastal flooding management perspective.

From an asset perspective, Table 4-4 summarises the number of assets at coastal flooding risk across all the sites for each hazard category and each planning horizon.

Table 4-4 Hazard category – Coastal Flooding – All Sites (448 samples)

	2024	2040	2060	2080	2100
H1	26	23	24	19	4
H2	54	40	36	31	16
H3	54	40	36	31	16
H4	73	61	54	43	29
H5	128	133	145	154	121
H6	155	165	185	203	221

For further details, Figure D-12 details each site's hazard category and planning horizon considered in this study. Figure 4-3 stacks the number of asset flooding over time in each hazard category.

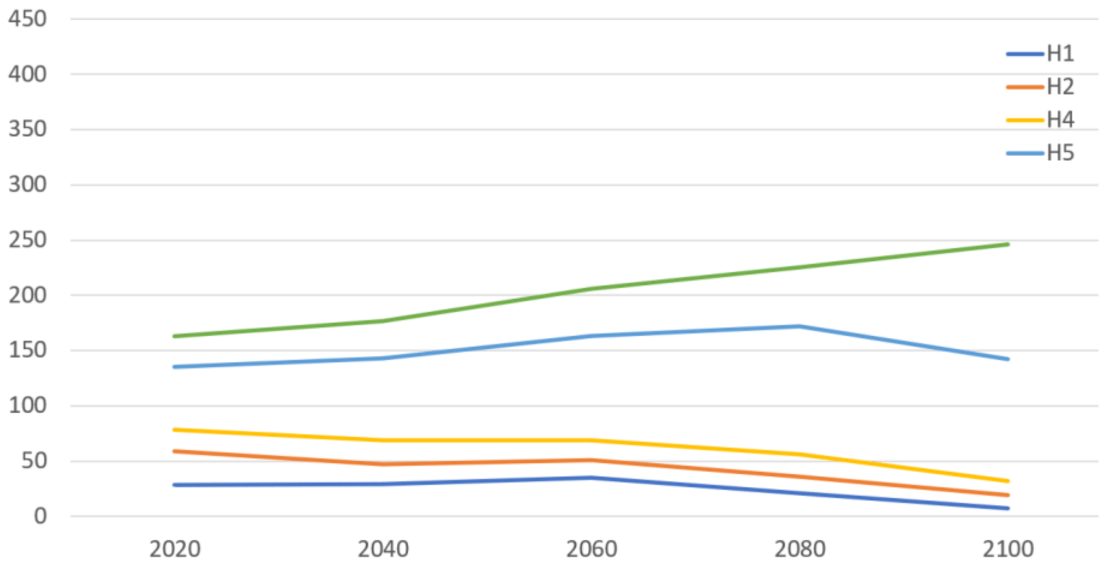

Figure 4-3 Asset flooding vulnerability

As the coastal flooding risk increases with rising sea levels, more assets become vulnerable to coastal flooding. Appendix D shows how individual assets are affected by coastal flooding over time for a representative number of assets around the closed landfill sites.

4.5 Coastal Erosion

Coastal erosion considers how the perimeter of each landfill is affected by coastal erosion when the perimeter of the site is submerged during coastal flooding events.

The landfill bund perimeter was defined as the 2020 coastal inundation extent already submerged at High Astronomical Tide. This defines a perimeter bund, which may be either existing, partially built as a revetment or levee or a virtual bund where a bund is not implemented, such as the Holloway closed landfill site.

The following properties are important to understand the capacity of the perimeter bund at each site:

- Geometry, including length, slope and height;
- Bund material composition;
- Exposure to inundation and flooding; and
- Exposure to wave actions.

The following notes summarise the status of perimeter bunds based on observations made during site inspections:

- **Portsmith** - mangrove forest and waterways on the landfill's southern side significantly attenuate coastal waves. A riprap shoulder has been installed along the perimeter road connected to Broughton Creek. The structure is generally in good condition.
- **Yorkeys Knob** - the site's northern edge, along Half Moon Creek, is protected by grass cover and mangroves and forms a protective embankment to the cap and waste.

- **Machans Beach** - the southern and eastern edge of the closed landfill, on the edge of the sport field, is covered by shrubs and trees covering the landfill embankment.
- **White Rock** - a riprap embankment that follows the perimeter road made of cobble and stones typically 300mm in size and has been built around the landfill area along Crowley Creek, in the mangrove. The mangrove is very dense and runs dry most of the day. The crest of the embankment is cut by a stormwater drainage channel, running perpendicular to the perimeter road, which are typically grouted. A rock toe is present in some areas. The revetment is typically in fair condition, with some rock missing and large cracks and voids developing in some sections of the grouted works.
- **Endeavour Park** - the riprap embankment along Lily Creek is generally in good condition, often covered with grass and debris.
- **Aeroglen** - the gully west of the site is covered with mangroves and is generally directly connected to the grass covering the fields
- **Mann Street** - the riprap revetment along Smith Creek is in good condition
- **Barlow Park** - the riprap revetment along Smith Creek is in good condition
- **Cairns Esplanade** - the seawall is in various conditions, with excellent condition to the north of the site where a bluestone seawall has been installed but only fair condition to the south of the site. The southern section geotextile underlay is visible in many areas, and stones are weathered and typically stacked in a pattern that encourages access through the structure while not providing compliant public access.
- **Holloways Beach** - has no edge protection and is a flat grass area growing within gravelly soil, and the mangrove forest along Richters Creek abuts the site.

Table 4-5 summarises key perimeter bund parameters for each site.

Table 4-5 Perimeter bund summary

Location	Bund Perimeter, m	Slope v:h	Typical material in most exposed areas	Condition Rating
Portsmith	2,091	1:2	Riprap	Good
Yorkeys Knob	1,257	1:2	Tall grass, mangrove	N/A
Machans	556	1:2	Shrubs, Casuarina	N/A
White Rock	1,086	1:1.5	Riprap	Fair
Endeavour	1,345	1:1.5	Riprap	Good
Aeroglen	1,564	1:10	Grass, mangrove gully	N/A
Mann Street	1,206	1:1.5	Riprap	Good
Barlow Park	1,160	1:1.5	Riprap	Good
Esplanade	3,401	1:1.5	Various seawall	Excellent to Fair
Holloways	476	Flat	Mangrove	N/A

Table 4-6 and Table 4-7 summarise the proportion of length of the bund subject to coastal inundation and flooding for the five-planning horizon considered in this assessment.

Table 4-6 Perimeter bund inundation

Location	2020	2040	2060	2080	2100
Portsmith	0%	16%	41%	65%	76%
Yorkeys Knob	0%	22%	30%	37%	52%
Machans	0%	9%	29%	43%	51%
White Rock	0%	10%	12%	19%	24%
Endeavour	0%	30%	53%	70%	91%
Aeroglen	0%	7%	12%	19%	32%
Mann Street	0%	0%	67%	80%	96%
Barlow Park	0%	0%	65%	85%	99%
Esplanade	0%	1%	7%	31%	64%
Holloways	0%	42%	64%	81%	91%

Table 4-7 Perimeter bund flooding

Location	2020	2040	2060	2080	2100
Portsmith	65%	71%	78%	85%	95%
Yorkeys Knob	6%	12%	22%	34%	59%
Machans	40%	43%	54%	59%	73%
White Rock	15%	18%	21%	32%	45%
Endeavour	63%	71%	83%	97%	100%
Aeroglen	11%	16%	23%	34%	73%
Mann Street	77%	85%	97%	100%	100%
Barlow Park	77%	85%	95%	99%	100%
Esplanade	80%	86%	95%	99%	99%
Holloways	43%	56%	82%	89%	98%

The coastal flooding hazard will affect over 95% of the perimeter of the Portsmith, Endeavour, Mann Street, Barlow Park, Esplanade, and Holloways closed landfill sites by 2100.

The Vellinga storm erosion profile was used to estimate the bund erosion potential without coastal protection works such as rip-rap structures. The Department of Environment and Science recommends this formula to estimate erosion prone area of sandy beaches as per Department of Heritage and Environment Protection guidelines for coastal hazard assessment (2013). As such, using this formula to estimate the erosion potential due to wave actions around the perimeter of the landfill site is likely to be conservative as solid waste is likely to be more resistant to erosion than clean sand. The results are helpful for comparative purposes.

For this assessment, the study considered that mangroves may be damaged during tropical cyclones and that some wave action could reach all embankments. As the sea level rises, the mangrove forest is likely to become more and more submerged, and this would typically result in thinning out the mangrove forest over time against the existing embankment. While this assumption is conservative, the waves considered were depth-limited at the toe of the embankment, which is often very shallow.

Table 4-8 shows the resulting erosion potential around the perimeter bund for a 100-year ARI tropical cyclone.

Table 4-8 Bund erosion potential due to coastal flooding (m^3)

	2020	2040	2060	2080	2100
Portsmith	810	1117	1,800	2,900	4,800
Yorkeys Knob	85	242	765	2,000	5,500
Machans	250	360	670	1,250	2,400
White Rock	210	275	400	900	1,800
Endeavour	210	290	450	720	1,000
Aeroglen	17	25	55	110	350
Mann Street	90	100	165	230	350
Barlow Park	90	100	165	230	350
Esplanade	45,000	74,000	120,000	200,000	300,000
Holloways	90	100	165	230	350

The Esplanade site is located in the coastal erosion prone area as defined by State mapping. As such, the potential risk of erosion to solid waste located along the foreshore is very high. The seawall protects the embankment, and the waste is unlikely to have been placed continuously and immediately on the beachfront, therefore, actual erosion risk is much lower at this site.

A rip-rap embankment protects the Portsmith, White Rock, and Endeavour sites from bund erosion. These revetments reduce the erosion potential during storms, especially if the rip-rap is maintained in functional conditions and the revetment design is sufficient for a large storm. The typical design standard revetment design usually considers a 50-year ARI storm and would include a lower sea level rise allowance, so these revetments cannot be entirely relied upon for coastal erosion mitigation without further upgrades.

The Aeroglen, Mann Street, Barlow Park, and Holloways sites are not at significant risk owing to site protection from waves, considering the topology of the site. The actual erosion potential at Mann Street and Barlow Park is low for these sites, considering that a rip rap revetment is installed along Smith Creek. The Endeavour site is likely to be similar.

The Yorkeys Knob and Machans sites are the most vulnerable to coastal erosion because there is no formal revetment edge along these sites. The erosion hazard increases significantly as the sea level rises. The vulnerability of each bund to coastal erosion is summarised in Table 4-9.

Table 4-9 Bund erosion vulnerability

	2020	2040	2060	2080	2100
Portsmith	Low	Low	Medium	Medium	Medium
Yorkeys Knob	Low	Medium	High	Extreme	Extreme
Machans	Medium	Medium	High	Extreme	Extreme
White Rock	Low	Low	Low	Low	Medium
Endeavour	Low	Low	Low	Low	Medium
Aeroglen	Low	Low	Low	Low	Low
Mann Street	Low	Low	Low	Low	Low
Barlow Park	Low	Low	Low	Low	Low

	2020	2040	2060	2080	2100
Esplanade	Extreme	Extreme	Extreme	Extreme	Extreme
Holloways	Low	Low	Low	Low	Low

4.6 Landfill Cap Scour

Coastal scour and cap failure (as defined in the glossary) considers how the landfill's surface is affected by hydraulic action when the site is submerged during coastal flooding events. Typically, this results in abrasion action on the cap of the landfill. Inundation and flooding extent for each landfill was measured from the 2020 coastal inundation extent.

Table 4-10 and Table 4-11 show the proportion of each site submerged by inundation or flooding for the five-planning horizons considered in this study.

Table 4-10 Inundation hazard as a percentage of landfill area

	2020	2040	2060	2080	2100
Portsmith	0%	1%	2%	3%	7%
Yorkeys Knob	0%	0%	1%	1%	4%
Machans	0%	0%	2%	3%	6%
White Rock	0%	0%	0%	0%	1%
Endeavour	0%	0%	2%	12%	41%
Aeroglen	0%	1%	2%	4%	6%
Mann Street	0%	0%	54%	66%	79%
Barlow Park	0%	0%	17%	40%	60%
Esplanade	0%	0%	0%	4%	22%
Holloways	0%	41%	70%	87%	95%

The Holloways, Mann Street, Barlow Park and Endeavour sites are likely to be substantially inundated by sea level rise by 2100. On the other hand, the White Rock, Yorkeys Knob, Machans, Aeroglen, and Portsmith sites have less than 10% inundation. The inundation area is still significant at Portsmith, with approximately 2ha of the site inundated, consisting of the perimeter road, stormwater, leachate drain, and sedimentation basin.

The Esplanade is at risk of inundation both from the open coast and the Esplanade road. Additionally, the stormwater drainage pits along the esplanade are deep and were observed during site inspections to be connected to the sea across the Esplanade.

Table 4-11 100-year ARI flooding hazard as a percentage of landfill area

	2020	2040	2060	2080	2100
Portsmith	3%	4%	7%	10%	13%
Yorkeys Knob	0%	0%	1%	2%	4%
Machans	3%	3%	6%	8%	15%
White Rock	0%	1%	1%	1%	2%
Endeavour	4%	9%	24%	58%	100%

	2020	2040	2060	2080	2100
Aeroglen	2%	3%	4%	6%	22%
Mann Street	61%	66%	75%	83%	96%
Barlow Park	28%	42%	54%	71%	90%
Esplanade	71%	79%	90%	97%	100%
Holloways	44%	64%	84%	92%	100%

The 100-year ARI coastal flooding risk at Barlow Park, Mann Street, Aeroglen, Endeavour, Esplanade and Holloways spreads over 90% of the surface of these sites. During a 100-year cyclone storm tide event, submerging the landfill caps can lead to abrasion of the landfill cap as well as cracks and potholing.

The material eroded from the cap can be collected in sedimentation ponds around the perimeter of the landfill site. The closed landfill caps are covered by grass and topsoil and are sloped, which effectively controls soil erosion for most rainfall conditions. Additionally, sediment basins can be built to intercept stormwater runoff on the edges of the landfill. Only the Portsmith closed landfill site has sediment basins to manage the landfill cap sediment loss from stormwater scour. All other sites discharge stormwater runoff and sediment load arising from the abrasion of topsoil directly to the receiving environment.

An erosion assessment of each landfill cap has been carried out for the closed landfill cap using the Hjulström diagram. The Hjulström diagram represents the relationship between water flow velocity and the sediment particle size that the water can transport. It is a useful tool in geomorphology and sedimentology to understand the processes of sediment erosion, transportation, and deposition by flowing water. While the Hjulström diagram simplifies real-world sediment transport, it indicates which type of cover would be stable. For coastal flooding, flow velocities have been assumed to be supercritical. This corresponds to swash-like actions on the shoreline when waves are overtopping and breaking on the foreshore and in the submerged area of the landfill cap. While this may be conservative, lawn cover may not be tolerant to saltwater intrusion due to coastal inundation and significant work may be required to rehabilitate these lawns following flooding.

Table 4-12 details the result of the scour assessment and shows the type of soil material armouring required to control soil losses for uncovered soil conditions. In this assessment, the diameter of sand material is typically less than 1mm, gravel spans from 1 to 10mm, pebbles from 10 to 100mm and cobbles are larger than 100mm. Effectively, a “cobble cover” corresponds to riprap armour.

Table 4-12 Soil material stability to coastal flooding scour

Site	Sub-Area / asset ID	Cap Type	2020	2040	2060	2080	2100
Portsmith	North area / 23	Topsoil and CCL	Pebble	Pebble	Pebble	Pebble	Pebble
Portsmith	East and South-East / 28	Topsoil and CCL	Pebble	Pebble	Pebble	Cobble	Cobble
Portsmith	West Side / 47	Topsoil and CCL	Pebble	Pebble	Pebble	Cobble	Cobble
Yorkeys Knob	Golf Fairway / 204	300 CCL + topsoil	Pebble	Pebble	Pebble	Cobble	Cobble
Machans	Sports field / 226	500 clean soil	Pebble	Cobble	Cobble	Cobble	Cobble
White Rock	/ 251	300 CCL+ 250 topsoil min	Cobble	Cobble	Cobble	Cobble	Cobble

Site	Sub-Area / asset ID	Cap Type	2020	2040	2060	2080	2100
Endeavour	Cap / 291	0.25 topsoil min	Sand	Gravel	Pebble	Pebble	Pebble
Aeroglen	Sports field / 325	100 topsoil min.	Pebble	Pebble	Cobble	Cobble	Cobble
Mann Street	Cap / 346	100 topsoil min.	Sand	Sand	Cobble	Cobble	Cobble
Barlow Park	Cap / 395	100 topsoil min.	Sand	Sand	Cobble	Cobble	Cobble
Esplanade	Cap / 434	100 topsoil min.	Pebble	Pebble	Pebble	Cobble	Cobble
Holloways	Cap /448	100 gravel	Pebble	Pebble	Pebble	Pebble	Pebble

All sites appear to be vulnerable to cap failure. By 2100, all closed landfill caps susceptible to coastal flood would require some riprap armour except Endeavour Sports Fields and the Holloways Accacia Street Park.

4.7 Leachate and groundwater

Landfill leachate can be influenced by surface water (from stormwater intrusion and seawater contamination) and groundwater infiltration. Leachate seepage to groundwater or the receiving water environment (creeks and sea) can be captured via a leachate collection system designed to collect the landfill groundwater for treatment through mechanical pumping.

The preliminary characterisation of each landfill site in Table 2-1 included several parameters related to:

- Geology;
- Surface water systems nearby;
- The extent of Landfilling (i.e., size and age);
- Form of any landfill liners;
- Leachate collection systems; and
- Permeability and capping.

Portsmith and White Rock have liner and leachate collection systems. However, these systems are vulnerable to coastal inundation and flooding as follows:

- At Portsmith, the blockwork around the surcharge pond will likely be overtopped by the 100-year ARI coastal flood from 2040 onward. The leachate pumping system appears to be inundated by seawater during high tides by 2080. Figure E-3 and Figure E-4 show the inundation and flooding of the Portsmith leachate pump station.
- At White Rock, the 100-year ARI coastal flood levels appear to intersect the floor of the pumping station by 2100. The stormwater perimeter drain is vulnerable to coastal flooding from 2020. Figure E-10 and Figure E-13 show the inundation and flooding of two pump stations.

Further surveys, including topological surveys using accurate surveying techniques, should be carried out for these specific assets to determine their vulnerability.

5 RISK ASSESSMENT

5.1 Introduction

A risk assessment was developed for each landfill site. The risk assessment defines the degree of impact coastal hazards will likely have on each site over the planning timeframe. The risk level is the magnitude of coastal hazard expressed in terms of the combination of vulnerability, consequence, and likelihood as outlined in the “Queensland Emergency Risk Management Framework” (QERMF). This is displayed diagrammatically in Figure 5-1.

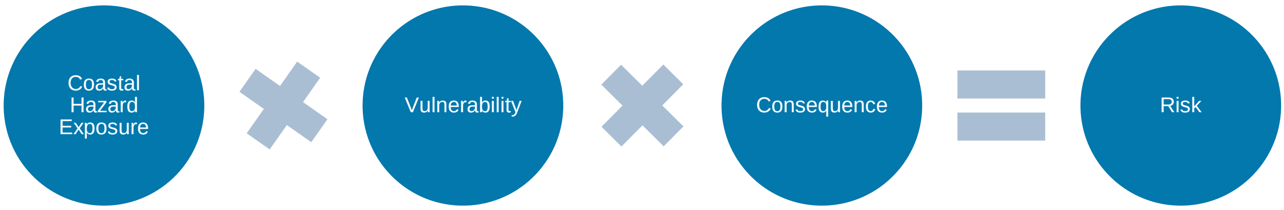

Figure 5-1 Vulnerability Assessment Components

The coastal hazard exposure measures each site’s exposure over the five planning horizons for each coastal hazard, including coastal flooding, inundation, erosion and scour. The vulnerability of each site depends on several factors, including landfill type, volume, distance to sensitive receptors and potential cost of relocation. The consequence of the coastal hazards for each landfill is related to the severity of coastal flooding, inundation, erosion and scour at each site over the five planning horizons considered in this study. The QERMF risk calculator (reproduced in Figure 5-2) was used for the coastal landfill risk assessment. The risk calculator scales from 1 to 13 and ranges from Very Low (VL), Low (L), Moderate (M), High (H) to Extreme (E).

Likelihood (X)		Rare (1)					Unlikely (2)					Possible (3)					Likely (4)					Almost Certain (5)				
Vulnerability (Y)		V.Low (1)	Low (2)	Mod (3)	High (4)	Extr (5)	V.Low (1)	Low (2)	Mod (3)	High (4)	Extr (5)	V.Low (1)	Low (2)	Mod (3)	High (4)	Extr (5)	V.Low (1)	Low (2)	Mod (3)	High (4)	Extr (5)	V.Low (1)	Low (2)	Mod (3)	High (4)	Extr (5)
Consequence (Z)	INSIGNIFICANT (1)	VL1	VL2	VL3	L4	L5	VL2	VL3	L4	L5	L6	VL3	L4	L5	L6	M7	L4	L5	L6	M7	M8	L5	L6	M7	M8	H9
	MINOR (2)	VL2	VL3	L4	L5	L6	VL3	L4	L5	L6	M7	L4	L5	L6	M7	M8	L5	L6	M7	M8	H9	L6	M7	M8	H9	H10
	MODERATE (3)	VL3	L4	L5	L6	M7	L4	L5	L6	M7	M8	L5	L6	M7	M8	H9	L6	M7	M8	H9	H10	M7	M8	H9	H10	H11
	MAJOR (4)	L4	L5	L6	M7	M8	L5	L6	M7	M8	H9	L6	M7	M8	H9	H10	M7	M8	H9	H10	H11	M8	H9	H10	H11	E12
	CATASTROPHIC (5)	L5	L6	M7	M8	H9	L6	M7	M8	H9	H10	M7	M8	H9	H10	H11	M8	H9	H10	H11	E12	H9	H10	H11	E12	E13

Figure 5-2 QERMF Risk Calculator

This risk calculator is compatible with AS/NZS ISO31000:2018 requirements and includes 5 categories of hazard likelihood, vulnerability, and consequence.

The exposure of each site to hazards has been detailed in Section 4. Section 5.2 details the coastal hazard exposure, and Sections 5.3 and 5.4 assign vulnerability ratings and consequences of submergence (flooding or inundation) for each site. Section 5.5 summarises the result of the risk assessment.

5.2 Exposure/Likelihood Rating

The exposure/likelihood of identified assets represents the likelihood of coastal hazards impacting each landfill site. That is, the probability of impacting each site over time. The likelihood scale adopted for this study is presented in Table 5-1 and shows how ARI relates to the occurrence of events.

Table 5-1 Exposure/Likelihood Rating

Likelihood Rating	Annual Exceedance Probability	Average Recurrence Interval (ARI)
Almost Certain	>63%	Less than 1 year
Likely	10 - <63%	1 to <10 years
Unlikely	1 - <10%	10 to <100 years
Rare	0.1 - <1%	100 to <1,000 year
Very Rare	<1%	1,000 to <10,000year
Extremely Rare	Less than 0.01% per year	10,000 years or more

The likelihood ratings for each coastal hazard and each planning horizon have been assigned as follows:

- The coastal inundation hazards will be "Almost Certain" for each planning horizon considered.
- The coastal flooding hazards associated with storm tide and the coincident coastal erosion and scour hazards are "Rare" for any given year. However, the threat increases over time. Therefore, this hazard has been expressed as a function of the elapsed time of exposure to the 100-year ARI storm tide event for each planning horizon. This corresponding encounter probability was calculated using the Borgman formula, as outlined in the "Guideline for Responding to the Effects of Climate Change in Coastal and Ocean Engineering". Table 5-2 shows the encounter probability and exposure rating of a 100-year ARI storm tide event over the five-planning horizons and for the year 2150.

Table 5-2 Coastal flooding encounter probability

	2020	2040	2060	2080	2100	2150
100-year ARI storm tide	1%	18%	33%	45%	55%	73%
Exposure rating	Rare	Likely	Likely	Likely	Likely	Almost Certain

This calculation estimates a 55% likelihood for at least one 100-year ARI storm tide event to occur or to be exceeded by 2100. The compounding effect of coastal landfills exposed to a 100-year ARI storm tide over 80 years, from 2020 to 2100, increases the exposure rating from Rare to Likely. Based on that scaling, by 2150, the exposure rating becomes "Almost Certain".

Table 5-3 shows the resulting subset of the risk calculator used for this study, extracted from the QERMF risk calculator.

Table 5-3 Closed Landfill Coastal Hazard - Risk Calculator

Vulnerability		Likelihood									
		Rare					Likely				
		VL	L	M	H	E	VL	L	M	H	E
Consequence	Insignificant	VL1	VL2	VL3	L4	L5	VL3	L4	L5	L6	M7
	Remarkable	VL2	VL3	L4	L5	L6	L4	L5	L6	M7	M8
	Severe	VL3	L4	L5	L6	M7	L5	L6	M7	M8	H9
	Major	L4	L5	L6	M7	M8	L6	M7	M8	H9	H10
	Catastrophic	L5	L6	M7	M8	H9	M7	M8	H9	H10	H11

5.3 Vulnerability Rating

Landfill vulnerability to coastal hazards depends on the extent of contamination, the toxicity of landfill material and the proximity to sensitive receiving coastal environments such as natural habitats, fisheries, bathing waters, etc. Solid waste contamination of the receiving environment is of concern. While some waste material may become inert over time, the density of some waste, such as plastics or organic matter, may be dispersive. Leachate may also disperse in the soil and groundwater as toxicants diffuse out of the landfill.

The vulnerability of each landfill site was determined as a function of landfill volume, waste type and distance to sensitive receptors. Table 5-4 shows the rating system (on a scale from Very Low to Extreme) used for the landfill site based on the rating proposed by Brand (Brand and Spencer, 2018).

Table 5-4 Vulnerability Rating

	Very Low (VL)	Low (L)	Moderate (M)	High (H)	Extreme (E)
Landfill volume, m^3	10,000	40,000	200,000	1,000,000	>1m
Landfill waste type	Inert	Household or commercial	Industrial	Special waste	Liquid sludge or unknown
Distance to Fish Habitat Area, km	1	1	0.5	0.1	0

Table 4-3 provided information for landfill volume and landfill type. Solid waste can become inert over time. As such, the landfill type rating was adjusted for 60 years after landfill closure from Low to Very Low for household waste. This period is twice the period used for the statutory renewal of EA for closed landfill sites. Some residual contamination levels are still likely after such a period.

The downstream distance to the Fish Habitat Area (FHA) was considered to assess proximity to sensitive receptors. Several closed landfill sites drain into canals but also to areas declared as Matters of State Environmental Significance (MSES, either wetland or vegetation), which also have essential conservation values.

The higher vulnerability rating was assigned to each closed landfill site for each planning horizon. The resulting vulnerability ratings are shown in Table 5-5.

Table 5-5 Vulnerability Analysis

		Portsmith	Yorkeys Knob	Machans	White Rock	Endeavour Park	Aeroglen	Mann Street	Barlow Park	Esplanade	Holloways
Volume		E	M	M	H	H	M	M	VL	VL	VL
Type	**2020**	L	L	L	L	L	L	L	VL	VL	L
	2040	L	L	L	L	VL	L	VL	VL	VL	VL
	2060	L	VL	VL	L	VL	VL	VL	VL	VL	VL
	2080	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
	2100	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
FHA proximity		H	E	L	H	VL	L	VL	VL	E	H
Total Rating		**E**	**E**	**M**	**H**	**H**	**M**	**M**	**VL**	**E**	**H**

All vulnerability ratings were found to be “Extreme”, except:

- Endeavour Park is located across Lily Creek (an urban drain lined with rock revetment), a regulated vegetation and wildlife habitat MSES;
- Machan Beach is not directly abutting a FHA but neighbours a regulated vegetation and wildlife habitat MSES;
- Aeroglen is not directly abutting a FHA but is 100m upstream from a wildlife habitat MSES; and
- Mann Street neighbours a regulated vegetation and wildlife habitat MSES.

5.4 Consequence Rating

Consequence ranks the physical impact of each coastal hazard at each landfill site. Consequence ranges from Insignificant (I), Remarkable (R), Serious (S), Major (M) to Catastrophic (C) and changes over the planning horizon as the coastal hazard evolves.

For each landfill site and planning horizon, the coastal flood hazard was estimated as a proportion of the landfill area submerged during the 100-year ARI storm tide event. Insignificant flooding was set at 1% of the landfill site, remarkable at 5%, serious up to 15%, major below 50% and catastrophic when over 50% of the site is flooded. The consequence of storm tide submerging the site includes various processes such as venting of pockets of landfill gas, deformation of the landfill surface through voids collapsing, buoyancy of low-density solid waste lifting the cap of the landfill, release of leachate at the surface of the landfill and damage of grass cover particularly where the landfill cap cover is not salt tolerant.

The consequence of coastal inundation due to sea level rise is measured on an order of magnitude scale, starting at 5m^2 (Insignificant rating) and increasing to 0.5ha (catastrophic rating) coastal inundation area. The inundation would have consequences similar to the coastal flooding processes described above (LFG venting, void collapse, cap lifting, leachate release, grass die-back, etc.). Inundation would first occur repetitively, during high tide, before becoming permanent.

The width of the erosion of the bund due to storm tide hydraulic actions around the landfill perimeter is also rated on a sliding scale from 0.1m to 3m. When suited, the erosion potential estimated in Table 4-8 was modified to account for revetment and seawalls developed along the perimeter of the landfill sites. A reduction of erosion potential by 95% was considered when the asset condition was Excellent, 90% for Good and 80% for Fair. When the resulting erosion width is smaller than 0.3m, this is typically less than the landfill cap thickness and the consequence rating was assigned to be either Insignificant or Remarkable. While this erosion width is small, the length of the bund perimeter at risk of erosion can be quite large, so the volume of soil eroded and solid waste at risk of erosion could be significant. An erosion width between 0.3m and 1.0m has been rated Serious, with solid waste likely to enter the receiving environment. An erosion width between 1.0m and 3.0m has been rated Major as the solid waste strata become increasingly exposed. An erosion width beyond 3.0m has been rated Catastrophic since most of the solid waste strata will be disturbed in such an event.

The potential for material to scour on the landfill cap is rated as Insignificant when sand grains are mobile but not gravel, Remarkable when gravel size particles are in motion, and Serious when pebble or small stones that can move at the landfill's surface. The mobility of cobblestones, and therefore riprap, has been rated Major. A Catastrophic rating is assigned when riprap is mobile and coastal flooding affects over 20% of the landfill cap.

Table 5-6 summarises the consequence ratings applied to all sites and planning horizons.

Table 5-6 Consequence Rating

	Criteria	Insignificant (I)	Remarkable (R)	Serious (S)	Major (M)	Catastrophic (C)
Flood	Landfill surface flooded (%)	1%	5%	15%	50%	>50
Inundation	Permanently submerged surface (m^2)	5	50	500	5,000	>5,000
Erosion	Bund erosion potential (m)	0.1	0.3	1	3	>3
Scour	Cap scour potential	Sand	Gravel	Pebble	Cobble	Cobble >20% flood

Table 5-7 summarises the results of the consequence analysis. The higher consequence rating was assigned to each closed landfill site for each planning horizon.

The consequence of flood hazard dominates the ratings at most sites.

The results shows that the consequence of coastal hazards on landfills at the Cairns Esplanade is Catastrophic in present-day conditions. The high rating is due to substantial coastal erosion hazards along the Cairns foreshore. While a seawall mitigates this coastal erosion hazard, the seawall condition is not Excellent everywhere and also, the seawall may not be of sufficient engineering standard.

The Mann Street site consequence rating is also Catastrophic because the 100-year ARI storm tide substantially submerges the site.

The consequence of coastal hazards reaches a Catastrophic rating for all sites by 2100. While the consequences associated with flood hazards often anticipate the inundation hazards, only Yorkeys Knob, Machan, White Rock and Aeroglen sites are not reaching Catastrophic inundation hazard ratings by 2100. This underpins that these four sites are more resilient to climate change than others.

Table 5-7 Consequence Analysis

		2020	2040	2060	2080	2100
Portsmith	Flood	S	S	S	S	M
	Inundation	I	M	M	C	C
	Erosion	R	R	S	S	S
	Scour	S	S	S	M	M
	Consequence Rating	**S**	**M**	**M**	**C**	**C**
Yorkeys Knob	Flood	I	I	I	R	R
	Inundation	I	S	S	M	M
	Erosion	M	C	C	C	C
	Scour	S	S	S	S	S
	Consequence Rating	**M**	**C**	**C**	**C**	**C**
Machans Beach	Flood	L	L	M	M	M
	Inundation	I	S	S	M	M
	Erosion	M	C	C	C	C
	Scour	S	M	M	M	M
	Consequence Rating	**M**	**C**	**C**	**C**	**C**
White Rock	Flood	I	I	I	R	R
	Inundation	I	R	S	S	S
	Erosion	R	R	S	C	C
	Scour	I	R	S	S	M
	Consequence Rating	**R**	**R**	**S**	**C**	**C**
Endeavour Park	Flood	R	S	M	C	C
	Inundation	I	M	M	C	C
	Erosion	I	R	R	R	R
	Scour	I	R	S	S	S
	Consequence Rating	**R**	**M**	**M**	**C**	**C**
Aeroglen	Flood	R	R	R	S	M
	Inundation	I	S	M	M	M
	Erosion	S	S	S	S	C
	Scour	S	S	M	M	M
	Consequence Rating	**S**	**M**	**M**	**M**	**C**

		2020	2040	2060	2080	2100
Mann St	Flood	C	C	C	C	C
	Inundation	I	I	C	C	C
	Erosion	M	M	C	C	C
	Scour	I	I	C	C	C
	Consequence Rating	**C**	**C**	**C**	**C**	**C**
Barlow Park	Flood	M	M	C	C	C
	Inundation	I	I	C	C	C
	Erosion	I	I	I	I	R
	Scour	I	I	C	C	C
	Consequence	**M**	**M**	**C**	**C**	**C**
Cairns Esplanade	Flood	C	C	C	C	C
	Inundation	I	R	S	M	C
	Erosion	C	C	C	C	C
	Scour	R	R	R	C	C
	Consequence Rating	**C**	**C**	**C**	**C**	**C**
Holloways Beach	Flood	M	C	C	C	C
	Inundation	I	M	M	C	C
	Erosion	M	M	M	M	M
	Scour	R	R	R	R	R
	Consequence Rating	**M**	**C**	**C**	**C**	**C**

5.5 Risk analysis

The risk calculator of Table 5-3 and the exposure, vulnerability and consequence rating determined in Sections 5.2, 5.3 and 5.4 were used to calculate the risk associated with coastal hazards at each landfill site. Table 5-8 shows the Cairns landfill site's coastal risk analysis results over the five planning horizons.

Table 5-8 Risk Analysis

	2020	2040	2060	2080	2100
Portsmith	M7	M8	H10	H11	H11
Yorkeys Knob	H9	H11	H11	H11	H11
Machans Beach	L6	M7	H9	H9	H9
White Rock	L5	L5	M8	H10	H10
Endeavour Park	L5	M7	H9	H10	H10
Aeroglen	L5	L6	M8	M8	H9
Mann St	L7	L7	H9	H9	H9
Barlow Park	L4	L4	M7	M7	M7
Cairns Esplanade	H9	H9	H11	H11	H11
Holloways Beach	M7	M8	H10	H10	H10

The coastal risk assessment shows that:

- Yorkeys Knob presently has the highest risk rating. This is due to a Major coastal erosion risk adjacent to the Half Moon Creek Fisk Habitat Area. This risk is mitigated by vegetation along the creek embankment, and this area needs careful management to control the loss of solid waste.
- The Cairns Esplanade also has a High Risk of coastal erosion hazard adjacent to the Trinity Inlet Fish Habitat Area. The solid waste visible along the foreshore (construction rubble including potential ACM, etc.) is apparent in the intertidal area and across some of the seawall's more dilapidated sections.
- Barlow Park has a risk rating below High by 2100. This landfill site is the least vulnerable to coastal hazards and is relatively far from sensitive receptors. Barlow Park appears to have a lower risk level than the other closed landfill sites.
- Portsmith and Holloways Beach share similar risk profiles despite their significant differences in size, age and development. These sites are typically more at risk than Machans, Endeavour Park, Aeroglen and Mann Street.
- All closed landfill sites reach a high-risk rating by 2100, except Barlow Park.

6 OPTION ANALYSIS

6.1 Identifying management options

The project aims to identify a preferred solution for managing coastal hazards at each site. A list of possible actions has been identified to improve the resilience of the landfill site to coastal hazards.

Historically, closed landfill sites are covered, capped, and monitored for extended periods. However, coastal hazards can significantly disrupt this process, particularly when coastal flooding or coastal inundation hazards affect the site as the climate changes. Several management options have been considered to mitigate such risks, including the removal of landfill waste to alternative sites. The Management options identified in the literature review (refer to Appendix A for a summary) can be grouped into four categories:

- **Monitoring** – The continuous or episodic monitoring, treatment and reporting associated with the management of landfill waste
- **Treatment** – Treatment of landfill waste and decontamination post-disaster clean-up and partial treatment of waste or Enhanced Landfill Mining to reduce landfill toxicity.
- **Protection** – Protection of the waste from coastal hazards such as hydraulic actions. This may include raising bund walls to defend the perimeter of the landfill (encapsulation via a coastal levee) or filling the top of the landfill site (protection via reclamation).
- **Removal** – Landfill waste material removal, either partial or complete removal

The “business-as-usual” scenario consists of monitoring and implementing measures outlined in each site’s Environmental Authority (EA) permit arising from an Environmentally Relevant Activity. Other options are additional to this baseline level and would be subject to feasibility studies, design, staging and budgeting. A “Do Nothing” scenario has also been listed for sites which are not subject to an EA.

Table 6-1 outlines nine potential treatment options in a long-list format to manage the sites.

The list is based on a literature review and may not fit all sites or be exhaustive or exclusive. Implementing a strategy for only a sub-section of a closed landfill site may also be possible. This is particularly salient to option 8-PRW, essentially a subset of 9-FRW.

From a practical point of view, 4-PWT and 5-ELFM have not been considered in the assessment. The volume of waste material in most landfill sites is small, and the complexity and maturity of these technologies are obstacles to wide-scale adoption. While these options have been removed from this assessment, they may be reconsidered in future studies.

Table 6-1 Potential management options

ID	Option	Description	Implications
	Monitoring		
1-DN	Do Nothing	Do nothing	No awareness of risk exposure. 'Do Nothing' would include statutory and episodic monitoring of the site and clean-up when a waste release occurs. Further actions may be triggered due to unexpected waste releases (e.g., a storm event) or environmental impacts (e.g., damage to ecosystems).
2-BAU	Business As Usual	Monitoring of landfill and of exposure to coastal hazards and (e.g., capping intact) carry-out targeted management actions	Obtaining consistent and meaningful monitoring data requires staff, budget, and program consistency. A detailed waste management strategy is implemented to control and mitigate waste release (either leachate or solid), if and when release occurs. Typically, this management option is regulated by an EA
	Treatment		
3-CU	Clean-up	Reactive removal of waste when release occurred, which could occur following coastal flood or inundation following option 1-DN or 2-BAU	Small solid waste is easily dispersed, capturing only parts of the release. Access to the clean-up site can be problematic and/or dangerous. Waste can disperse further than just in the nearfield and might impact on other Council areas or on areas of high ecological and/or amenity value. This activity may require frequent funding and can often become more expensive than proactive removal, reputational damage and likely prosecution.
4-PWT	Partial Waste Treatment	Treatment of the waste to remove toxic and harmful waste components	The residual waste left on site is treated on-site and can be discharged into the environment. This might be more applicable in locations where waste is pre-sorted. Finding suitable alternative landfill sites could be problematic.
5-ELFM	Enhanced landfill mining (ELFM)	Enhanced landfill mining is an emerging concept to enable circular economy and to offset costs of remediation by recovery of valuable land and/or resources contained within the landfill.	This is an emerging concept associated with the concept of Circular Economy, in which viability and costs would vary greatly, depending on the location, waste amount and composition. Experimental to a degree, so a risk to cost, time and performance of landfill treatment.
	Protection		
6-EW	Encapsulate and bund around waste	The landfill area is encapsulated behind an engineered coastal levee. Flooding may still occur, but water release can be controlled.	If failure/damage to the infrastructure occurs, uncontrolled waste release can occur. Combination with other treatment options, such as monitoring and repair if damage occurs, is desirable. Infrastructure can become submerged with sea level rise, especially when considering timeframes of over 100 years. Longer planning timeframes will need to be considered to avoid more costly clean-up efforts (due to increased volume and difficulty of access) later.
7-PW	Protect and reclaim over waste	Protecting the landfill site by raising the landfill above inundation and flood hazard and building an engineered revetment to protect the embankment.	The reclamation fill provides a physical mass/barrier to avoid solid waste release and treat leachate migration. Various options can be deployed for the revetment around the reclamation depending on the nature of hydraulic actions.
	Removal		
8-PRW	Partial removal of waste	Partial removal of toxic and harmful waste components and/or partial removal of waste that is at the highest risk of being exposed to coastal hazards (e.g., erosion).	While partial removal can manage "high-risk" situations it does not cover extreme risks. The untreated residual waste left on site may still be released into the environment. This management option may be more applicable in locations where waste is pre-sorted.
9-FRW	Full removal of waste	Complete removal of all waste from the site to another approved landfill site.	Very effective in removing the source from the environment, with no residual risk of waste release once completed. Very costly and finding suitable alternative landfill sites could be challenging.

6.2 Management options comparison

Management options are not all equivalent, and a hierarchy of options is proposed as follows (from preferred to least preferred):

- **Full Removal of Waste** – 9-FRW – when feasible and economical, this would be the most effective management option to manage coastal hazards. This management strategy may be scheduled over a long period of time.
- **Partial Removal of Waste** – 8-PRW – while this would be an effective management option to manage coastal hazards in most situations, partial removal can only be successful where the coastal hazard can be mitigated in the long term. Unfortunately, all sites investigated are vulnerable to climate change, particularly sea level rise. As such, the partial removal of waste would need to be continued over decades until waste is entirely removed. As such, this management option has been rolled into option 9-FRW. The removal management option was shortened to “removal” and covers both 9-FRW and 8-PRW.
- **Protect and reclaim over waste** – 7-PW – when feasible and economical, this option would effectively mitigate coastal hazards. There are many options to protect the landfill edge from coastal erosion. Nature Based Solutions, such as revegetation, including mangrove planting, may be suitable for sheltered sites, while riprap revetment or seawalls may be built for more exposed areas around the landfill perimeter. The “protect and reclaim over waste” management option was shortened to “reclaim” and covered 7-PW.
- **Encapsulate and bund around waste** – 6-EW - when feasible and economical. This option would effectively mitigate coastal hazards but would not address leachate contamination of surface water during floods. This management strategy may be less costly than the reclaim option as the volume of material to build a bund may be low compared to reclamation fill, particularly for high sea level rise and landfills with large surface area. Contaminated water may be released during the flooding of the landfill site. The encapsulate and bund around waste management option was shortened to “bund” and covered 6-EW.
- **The combination of 1-DN with 3-CU or 2-BAU with 3-CU represents the current form of management option.** These management options consist of waiting for coastal hazards before taking action. Some level of contamination is likely to occur because the coastal hazards are worsening over time. The cost of clean-up may become not only prohibitive but is also likely to lead to reputational damage. This management option was shortened to “Business as Usual” and covers combining 1-DN and 2-BAU with clean-up 3-CU when necessary.

6.3 Cost-Benefit Analysis

A comparative Cost-Benefit Assessment (CBA) was carried out for each landfill site and each planning horizon to determine the most likely strategy for each site. The waste removal, landfill reclamation and bunding management options were compared with the “business-as-usual” scenario, which consists of monitoring and maintaining the closed landfill sites in line with current statutory requirements and rectifying and cleaning up if the sites are degraded.

The cost of each management option was presented in net present value (NPV) terms. NPV is a standard economic analysis to compare options with time-variable costs and benefits. It allows for adjusting all future economic considerations to present-day dollars for a more direct comparison. This relates to the time-value of money, as planned expenses in the future are, in a sense, cheaper than equivalent costs today. A discount rate of 4% was used in the CBA analysis and unit rates for materials and assets. Further details on the CBA are provided in Appendix E.

The infrastructure development of each option cost (i.e., removal, reclaim, bund) was compared to BAU to establish a Cost-Benefit-Ratio (CBR). A CBR over 1 indicates that a management option provides a net benefit from the BAU position.

6.3.1 Cost of "business as usual" coastal hazard management

Clean-up following flooding or inundation underpins the "Business As Usual" management option, which relies on the existing capacity of each site to manage coastal hazards without further intervention. The cost of clean-up was estimated from the volume of landfill material eroded for the 100-year ARI storm flood (as per Table 4-8) plus the structure loss estimated from the sample stage damage curve of the Disaster Loss Assessment Guidelines (Australian Disaster Resilience Handbook Manual 27, Figure 1).

Table 6-2 shows the event-based exposure for the Esplanade and all other coastal landfill sites lumped together.

Table 6-2 100-year ARI storm tide NPV costs

Site	2020	2040	2060	2080	2100
Esplanade	$48,500,000	$33,600,000	$25,100,000	$19,300,000	$13,200,000
All other sites	$5,270,000	$1,340,000	$1,090,000	$1,180,000	$1,010,000

This table highlights the increased exposure of the Cairns Esplanade related to a commensurate coastal erosion hazard. Only a fraction of the Esplanade is likely to contain solid waste, so the NPV cost for the Esplanade site may be overestimated. However, cleaning up a commingled mix of waste sand and mud nearshore will likely be time-consuming and costly.

These BAU NPV costs were further adjusted to increase over time as the likelihood of the storm increased. This adjustment was scaled by the encounter probability of the storm and for each planning horizon considered. As such, the flood hazard accumulates over time, as per Table 5-2.

6.3.2 Economic benefits of waste removal

Table 6-3 provides the estimated comparative NPV costs for total waste removal at each landfill site considering the volume previously estimated.

Table 6-3 Cost of waste removal management options

Site	2020	2040	2060	2080	2100
Portsmith	$170,000,000	$77,600,000	$35,400,000	$16,200,000	$7,380,000
Yorkeys Knob	$16,000,000	$7,300,000	$3,330,000	$1,520,000	$694,000
Machans	$10,000,000	$4,560,000	$2,080,000	$951,000	$434,000
White Rock	$25,000,000	$11,400,000	$5,210,000	$2,380,000	$1,080,000
Endeavour	$22,500,000	$10,300,000	$4,690,000	$2,140,000	$976,000
Aeroglen	$6,200,000	$2,830,000	$1,290,000	$589,000	$269,000
Mann Street	$18,000,000	$8,210,000	$3,750,000	$1,710,000	$781,000
Barlow Park	$1,000,000	$456,000	$208,000	$95,100	$43,400
Esplanade	$1,000,000	$456,000	$208,000	$95,100	$43,400
Holloways	$200,000	$91,300	$41,700	$19,000	$8,680

Barlow Park, Esplanade and Holloways have smaller relocation costs than most landfill sites. The relocation of Portsmith, the largest site, is also an order of magnitude larger than the other closed landfill sites.

6.3.3 Economic benefits of landfill reclamation

Table 6-4 provides the estimated comparative NPV costs for reclamation of each landfill site. The parametric design of landfill reclamation is detailed in Appendix E. This management option consists of building up the foreshore level above the storm tide flooding level as well as building a revetment to mitigate coastal erosion hazards.

Table 6-4 Cost of reclamation management options

Site	2020	2040	2060	2080	2100
Portsmith	$849,000	$622,000	$442,000	$307,000	$238,000
Yorkeys Knob	$13,500	$14,300	$18,300	$20,800	$32,300
Machans	$73,000	$45,000	$36,600	$26,500	$26,300
White Rock	$55,400	$36,000	$25,100	$24,200	$26,400
Endeavour	$397,000	$357,000	$395,000	$452,000	$434,000
Aeroglen	$148,000	$96,300	$72,800	$57,600	$92,400
Mann Street	$4,480,000	$2,390,000	$1,360,000	$776,000	$497,000
Barlow Park	$2,440,000	$1,500,000	$922,000	$584,000	$402,000
Esplanade	$30,500,000	$16,000,000	$8,800,000	$4,780,000	$2,680,000
Holloways	$245,000	$162,000	$110,000	$68,300	$48,000

The reclamation of the Esplanade is extremely costly as the site's exposure to coastal flooding is vast. Only a fraction of the site is likely to have been built out of solid waste. Therefore, the cost of reclamation of this subset of the whole site may be much smaller.

6.3.4 Economic benefits of bunding

Table 6-5 provides the estimated comparative NPV costs for bunding each landfill site with a flood protection levee for each planning horizon investigated. The parametric design of the coastal levees is detailed in Appendix E.

Table 6-5 Cost of bunding management options

Site	2020	2040	2060	2080	2100
Portsmith	$1,390,000	$787,000	$467,000	$285,000	$203,000
Yorkeys Knob	$50,000	$49,100	$49,700	$44,400	$51,600
Machans	$165,000	$93,100	$63,400	$39,900	$32,700
White Rock	$143,000	$86,700	$54,600	$47,100	$43,400
Endeavour	$513,000	$302,000	$194,000	$132,000	$91,500
Aeroglen	$138,000	$104,000	$81,600	$69,300	$96,400
Mann Street	$623,000	$356,000	$224,000	$133,000	$88,800
Barlow Park	$788,000	$449,000	$273,000	$161,000	$105,000
Esplanade	$25,200,000	$13,200,000	$7,280,000	$3,930,000	$2,180,000
Holloways	$135,000	$91,400	$73,000	$46,200	$34,000

Comparing these results with Table 6-4 shows what type of infrastructure solution may benefit each site. Endeavour, Mann Street and Barlow Park are large sites more suitable for a levee than a reclamation, owing to the large volume of fill required to build up the site above the storm tide level at each planning horizon.

6.3.5 Comparison of management option

The Table 6-6 shows the management option with Cost Benefit Ratio higher than 1 for each site and planning horizon.

Table 6-6 Lower NPV strategy and CBR

Site	2020	2040	2060	2080	2100
Portsmith	BAU	BAU	BAU	BAU	BUND / 1.1
Yorkeys Knob	BAU	RECLAIM / 1.3	RECLAIM / 2.9	RECLAIM / 4.1	RECLAIM / 4.0
Machans	BAU	BAU	RECLAIM / 1.2	RECLAIM / 2.0	RECLAIM / 2.1
White Rock	BAU	BAU	RECLAIM / 1.0	RECLAIM / 1.6	RECLAIM / 1.6
Endeavour	BAU	BAU	BAU	BAU	BAU
Aeroglen	BAU	BAU	BAU	BAU	BAU
Mann Street	BAU	BAU	BAU	BAU	BAU
Barlow Park	BAU	BAU	BAU	BAU	BAU
Esplanade	BAU	RELOCATE / 13	RELOCATE / 38	RELOCATE / 95	RELOCATE / 167
Holloways	BAU	BAU	BAU	RELOCATE	RELOCATE / 3.1

At Esplanade, a detailed annualised estimate shows that relocating landfill waste will likely be effective after only 2 years of exposure. An ongoing strategy of mapping waste and removing waste appears beneficial for this site. Holloways also benefits from relocation, although only from 2068.

Yorkeys Knob would benefit from reclamation works, according to the analysis, by 2035. The actual form of the work is more related to revetment works since the volume of reclamation is relatively small compared to the coastal protection works required along Half Moon Creek. Careful monitoring of the site's coastal vegetation and maintenance of this vegetation via suitable Nature Based Solutions is likely to protect the bund for the foreseeable future. This strategy could play out for an extended period of time.

According to this economic model, Business As Usual appears economically sound at Portsmith, Endeavour, Aeroglen, Mann Street and Barlow Park until 2080. However, significant financial risk remains as the cost of remediation following a tropical cyclone could be onerous. Table 6-7 shows the CBR of a single storm tide event for each planning horizon.

Table 6-7 100-year ARI storm hazard and CBR

Site	2020	2040	2060	2080	2100
Portsmith	BAU	BAU	BAU	BUND / 1.4	BUND / 1.6
Yorkeys Knob	RECLAIM / 6.2	RECLAIM / 7.7	RECLAIM / 8.7	RECLAIM / 9.3	RECLAIM / 7.3
Machans	RECLAIM / 3.5	RECLAIM / 3.6	RECLAIM / 3.8	RECLAIM / 4.4	RECLAIM / 3.9
White Rock	RECLAIM / 3.8	RECLAIM / 3.5	RECLAIM / 3.3	RECLAIM / 3.5	RECLAIM / 3.0
Endeavour	BAU	BAU	BAU	BAU	BAU

Site	2020	2040	2060	2080	2100
Aeroglen	BAU	BAU	BAU	BAU	BAU
Mann Street	BAU	BAU	BAU	BAU	BAU
Barlow Park	BAU	BAU	BAU	BAU	BAU
Esplanade	RELOCATE / 47	RELOCATE / 73	RELOCATE 124	RELOCATE / 202	RELOCATE / 304
Holloways	BAU	RELOCATE / 1.0	RELOCATE 2.2	RELOCATE / 3.6	RELOCATE / 5.6

This shows significant benefits in upgrading the landfill sites early rather than later at Yorkeys Knob, Machans and White Rock and that relocation of the Holloway closed landfill would be cost-effective in less than 20 years.

6.3.6 Sensitivity testing and validity

Sensitivity testing was used to understand how comparative unit rates and discount rates influence the estimation of each management option and the CBR for all five planning horizons. The result of this analysis is provided in Appendix E. Overall, the results typically suggest that the results of Table 6-6 are conservative and that management options may be feasible earlier than suggested in Section 6.3.5.

There are significant uncertainties around comparative NPV estimates, and assumptions made grow with time. Cost estimates beyond 2040 should be viewed as indicative trends only.

With additional storm tide events and more detailed unit rates, a Monte Carlo analysis of CBA could be carried out to determine the assessment's accuracy more rigorously. Without such details, the accuracy of the CBA had been assumed to be no more than 50%. The strategies determined from the CBR have been revised more conservatively by extracting a CBR threshold of 0.5 rather than 1, and the analysis was further extended to 2150. This provides information on the nature of the ultimate management strategy, which is summarised in Table 6-8:

Table 6-8 Management option milestone with CBR>0.5

Site	Date	Management Option
Portsmith	2067	BUND
Yorkeys Knob	2028	RECLAIM
Machans	2035	RECLAIM
White Rock	2035	RECLAIM
Endeavour	2117	BUND
Aeroglen	2150	BAU
Mann Street	2150	BAU
Barlow Park	2109	RELOCATE
Esplanade	2020	RELOCATE
Holloways	2054	RELOCATE

Only Aeroglen and Mann Street appear to be viable on a BAU in the long term. The Aeroglen closed landfill site had the lowest 100-year ARI BAU costs and has a relatively low number of assets, while Mann Street closed landfill site BAU costs are high and costly to develop. The Appendix E discount rate sensitivity analysis shows that a bund at Mann Street could be the most cost-effective management option in the long term for this site.

6.4 Proposed management option

The proposed management options seek to provide a pathway for coastal hazard mitigation at each site. The risk assessment detailed in Section 5 was reviewed in the context of the BCA to determine suitable management options for each site.

While the CBA provides some useful contextual information on waste management strategy, it does not fully cover all costs, such as the intangible costs associated with environmental and social impacts caused by landfill waste dispersal in the environment or long-term costs associated with decontamination. The analysis demonstrates that the cost of waste removal may be high - but that the cost of recovering waste, remediating damages, and the cost of waste treatment following coastal flooding and inundation are signficant.

6.4.1 Portsmith

The Portsmith closed landfill site is exposed to high coastal hazard risks by 2060. This high risk is less than 50 years from the present, and the current level of risk is already Major; therefore, some level of mitigation is necessary. The CBA shows that bunding for this site is the most effective coastal hazard mitigation strategy.

However, a coastal levee around the site will be challenging to develop. The Portsmith railway shunting track and access road and services may impose practical limits to implementing the bunding option. Reclaiming and building a revetment around the landfill mound's perimeter may be more practical. The costs of reclaim and bund options are close and within the accuracy limit of the study. Also, the existing perimeter revetment could be upgraded as a transitional measure.

A protection management action should be planned for the Portsmith closed landfill site.

6.4.2 Yorkeys Knob

The Yorkeys Knob closed landfill site is exposed to High coastal hazard risks by 2040, and the unprotected edge of Half Moon Creek is vulnerable to erosion. The CBA shows that the most effective coastal hazard mitigation strategy is reclaiming, which consists of maintaining or upgrading vegetation cover or building a revetment along the Half Moon Creek embankment to reduce coastal hazards.

6.4.3 Machans

The Machans Beach closed landfill site was found to be exposed to High coastal hazard risks by 2060. The current level of risk is Low. The CBA shows that the most effective coastal hazard mitigation strategy is reclaiming.

Reclamation principally consists of building a revetment edge to the landfill site since the top of the landfill form is high and typically above flooding and inundation hazards over the following decades. Also, a substantial vegetation buffer around the site significantly reduces erosion hazard, the effect of which was not fully considered in the analysis.

6.4.4 White Rock

The White Rock closed landfill site is exposed to High coastal risk by 2080. This is a timeframe longer than 50 years, and the current level of risk is Low. The CBA shows that the most effective coastal hazard mitigation strategy is reclaiming. This would consist of filling the perimeter access road and upgrading the revetment.

6.4.5 Endeavour

The Endeavour Park closed landfill site is exposed to High coastal risk by 2060, and the current level of risk is Low. The CBA shows that the most effective coastal hazard mitigation strategy is Business As Usual for this site. This would still consist of maintaining and upgrading the revetment along Lily Creek and repairing the site following storm tide events.

6.4.6 Aeroglen

The Aeroglen closed landfill site is exposed to High coastal risk by 2100, and the current level of risk is Low. The CBA shows that Business As Usual is the most effective coastal hazard mitigation strategy. This consists of maintaining and repairing the site following storm tide events. The residual clean-up risk appears to be the lowest of all the sites investigated.

6.4.7 Mann Street

The Mann Street closed landfill site is exposed to High coastal risk by 2060, and the current level of risk is Low. The CBA shows that Business As Usual is the most effective coastal hazard mitigation strategy. This consists of maintaining and repairing the site following storm tide events. The residual clean-up risk is also much higher than the Aeroglen site and this site is located on the periphery of the Cairns CBD.

6.4.8 Barlow Park

The Barlow Park closed landfill site is exposed to Major coastal risk by 2100, and the current level of risk is Low. The CBA shows that Business As Usual is the most effective coastal hazard mitigation strategy. The BAU consists of maintaining and repairing the site following storm tide events and removing waste on an ad-hoc basis since the volume of waste appears to be limited. The removal of waste was found to be economically justifiable in the sensitivity assessment.

6.4.9 Esplanade

The Cairns Esplanade closed landfill site is already exposed to High coastal risk. The CBA shows that the most effective coastal hazard mitigation strategy is waste removal by 2040. This site is by far the most exposed and vulnerable of all sites. The seawall condition is varied and may not be engineered to manage coastal erosion in a major Tropical Cyclone along the Esplanade Precinct.

6.4.10 Holloways

The Holloways closed landfill site is exposed to High coastal risk by 2600, and the current level of risk is Major. The CBA shows that the most effective coastal hazard mitigation strategy is Business As Usual for this site. This consists of maintaining and repairing the site following storm tide events.

7 RECOMMENDATIONS

Recommendations for each landfill site are provided below. Since the 1937 cyclone, the Cairns region has experienced several events without substantial storm tide flooding. A major disaster would stretch Council's capability to the limit and would likely require State intervention. Such intervention would be most effective when local information and skills are available to guide recovery efforts. Post-cyclone clean-up and recovery efforts include the treatment of a substantial additional volume of waste due to debris and damaged goods and infrastructure.

A monitoring and investigation program related to ongoing management of the Cairns Closed Landfill Sites should be commensurate with the risk outlined in Table 6.2. A budget proportional to this risk, in the range of 2 to 10 percent, should be assigned to gather information and build local expertise within Council necessary to monitor, report, plan and manage the delivery of future risk mitigation works, either pre or post-disaster. This would be additional to the existing budget necessary to maintain the Environmental Authorities. Council should retain and secure internal skills and capacity to manage the coastal hazard risks. The monitoring budget could inform the mapping of solid waste extent and better understand water contamination risk (including leachate) to guide future management.

This study of the long-term coastal adaptation pathways for Cairns' closed landfill sites should be updated regularly. The accuracy of the study is affected by:

- Low-level information on flooding for a broader range of storm events. With additional storm tide events, a Monte Carlo CBA analysis could be carried out to more rigorously determine the long-term damage and infrastructure assessment.
- The extent and toxicity of some of the site appears to not be fully understood or documented. Further exploration and investigation would allow for a detailed assessment and improve the study recommendations.
- Permit conditions for infrastructure development will be essential and feasibility studies should investigate such considerations.

Therefore, this study validity is considered to be no more than 10 to 15 years.

7.1 Portsmith

The Portsmith closed landfill site was found to be exposed to High coastal hazard risks by **2060**, and the CBA shows that coastal protection works are economically sound for this site.

A feasibility study for coastal protection work should be developed. This would include identifying planning constraints, determining the alignment of coastal protection works, service modification and requirement (stormwater drainage, leachate system, etc.) and the preliminary engineering design of coastal protection works in stages up to 2100.

In the meantime, sediment traps around the site were found to be shallow during the site visit, and those should be cleaned to improve the adaptative capacity for extreme storms. High rainfall run-off may erode the cap and it would be helpful to maintain an erosion buffer onsite. Cleaning up the sediment pond reduces the cost of cleanup post-disaster.

Various plastic bails are stored at the facility, and immersion and damage of these could release such contaminants in the receiving water. A more robust cyclone-proof fence would net this material, reducing the release of contaminants and preventing other floating debris from reaching the waterways. An upgrade is therefore proposed for Portsmith perimeter fences.

Some stormwater drainage infrastructure, monitoring stations and telemetry along the site perimeter are vulnerable to storm tide inundation, and such assets would benefit from upgrades. This should be a topic of a specific vulnerability assessment informed by a local coastal hazard assessment, including the leachate pumping system.

Buildings at this site include the Material Recovery Facility (MRF) and the Recycled Glass Facility, which are both vulnerable to coastal hazards. For instance, the conveyor in the MRF is likely at risk of flooding. Both sites would benefit from a specific coastal hazard assessment within the confines of the buildings. This assessment could be carried out using the existing 3D model digital twins. Retrofitting electrical and mechanical equipment could also reduce the building's vulnerability. This may include lifting electrical switchboards, changing the configuration of mechanical drives, providing an elevated landing for site equipment such as forklifts, etc.

Such actions would allow the use of the site following a disaster to process landfill waste generated by such events, markedly improving Cairns's resilience to tropical cyclones.

7.2 Yorkeys Knob

The Yorkeys Knob closed landfill site was found to be exposed to High coastal hazard risks by **2040**, and the CBA shows that the most effective coastal hazard mitigation strategy is reclaiming, which may be carried out via a combination of Nature Based Solutions and revetment works.

A significant vegetation buffer along the landfill site embankment intersects the Half Moon Creek estuary. This high and steep slope is covered with significant vegetation, which has mitigated erosion for several decades. Maintaining a vegetated buffer is likely to be effective for a considerable period of time. It is recommended to maintain and protect the existing vegetation and carry out mangrove restoration to enhance the erosion protection provided by the natural vegetation. While this may not be the most direct approach, a Nature Based Solution (NBS) is a likely suitable outcome in the medium term, considering the environmental values of Half Moon Creek. Such an approach may not work for the whole embankment.

A design and adaptation plan should be prepared for Nature-Based Solution protection works to be implemented on site as soon as possible since the coastal risk is already High.

7.3 Machans

The Machans Beach closed landfill site was found to be exposed to High coastal hazard risks by **2060**, and the CBA shows that the most effective coastal hazard mitigation strategy is reclaiming for this site, which consists of preventing erosion of the sports field embankment.

A substantial vegetation buffer around the site significantly reduces erosion hazard, which is not fully considered in the risk analysis. Maintaining this buffer is likely to be effective, even though the existing embankment slope around the Machans Beach sports field shows signs of erosion and deterioration. Therefore, it is recommended to protect, maintain, and further develop this existing vegetation to stabilise embankment erosion. A local design and adaptation plan should be formulated to prepare for further erosion protection works (NBS and/or revetment works) in the long term.

7.4 White Rock

The White Rock closed landfill site was found to be exposed to High coastal risk by **2080**, and the CBA shows that the most effective coastal hazard mitigation strategy is filling the perimeter access road and upgrading the revetment over time.

Stormwater drainage infrastructure, monitoring stations and telemetry along the site perimeter are vulnerable to storm tide, and such assets would benefit from upgrades. This could be carried out as part of a maintenance program, as the infrastructure at the White Rock closed landfill is aging. A design and adaptation plan should be prepared for further protection and revetment works.

7.5 Endeavour

The Endeavour Park closed landfill site was found to be exposed to High coastal risk by **2060**, and the CBA shows that the most effective coastal hazard mitigation strategy is maintaining and upgrading the revetment along Lily Creek and repairing the site following storm tide events.

There are several flood-prone assets nearby, and the site is located on the perimeter of the Cairns CBD. Therefore, upgrading this site with a coastal levee could benefit the closed landfill site and the wider community.

Before the next iteration of the closed landfill coastal hazards risk analysis, additional information should be gathered to improve the accuracy of risk management outcomes. The extent of the landfill is somewhat understood for this site, as there are some surveys available for the cap. However, this information is less systematic than a Ground Penetrating Radar (GPR) survey. Also, the toxicity of the waste and leachate diffusion are not well understood. Therefore, an investigation should determine how successful the liner is, which will require groundwater monitoring and testing.

7.6 Aeroglen

The Aeroglen closed landfill site was found to be exposed to High coastal risk by **2100**, and the CBA shows that the most effective coastal hazard mitigation strategy is maintaining and repairing the site following storm-tide events.

Once this study expires, a further waste management strategy would benefit from additional information and studies to better manage risk.

This study did not document the extent of landfill including configuration and cells. The solid waste extent should be surveyed to manage this site in the long term. This could include a systematic Ground Penetrating Radar (GPR) survey and test pits for ground truthing. Also, the toxicity of the waste and leachate diffusion are not well understood. Therefore, an investigation should assess how successful the liner is, and this would require some additional groundwater monitoring and testing.

Such investigations should be completed before the next strategic assessment.

7.7 Mann Street

The Mann Street closed landfill site was found to be exposed to High coastal risk by **2060**, and the CBA shows that the most effective coastal hazard mitigation strategy is maintaining and repairing the site following storm-tide events.

A high coastal hazard risk affects the Mann Street site within the next 50 years. Therefore, further information should be gathered before the next closed landfill site strategic assessment.

This study did not document the extent of landfill including configuration and cells. The solid waste extent should be surveyed to manage this site in the long term. This could include a systematic Ground Penetrating Radar (GPR) survey and test pits for ground truthing. Also, the toxicity of the waste and leachate diffusion are not well understood. Therefore, an investigation should assess how successful the liner is, and this would require some additional groundwater monitoring and testing in Smith Creek.

7.7.1 Barlow Park

The Barlow Park closed landfill site was found to be exposed to Major coastal risk by **2100**, and the CBA shows that the most effective coastal hazard mitigation strategy is removing waste on an ad-hoc basis since the volume of waste appears to be limited and the risk is lower than High.

Monitoring the receiving water in Smith Creek may assist in determining the toxicity of the waste material. This monitoring should coincide with the Mann Street monitoring, as the assumption formulated in this study that the waste material at Barlow Park is inert may be too optimistic. Therefore, such monitoring should be completed before the next strategic assessment.

7.8 Esplanade

The Cairns Esplanade closed landfill site was found to **already** be exposed to High coastal risk, and CBA shows that the most effective coastal hazard mitigation strategy is waste removal.

A detailed site investigation is necessary to support systematic waste removal since the volume of waste appears to be limited. In the meantime, ad-hoc waste removal is cost-effective because clean-up costs of commingled waste with coastal sand and mud are likely to be prohibitive. The solid waste extent should be surveyed to support waste removal at this site as soon as possible. This could include a systematic Ground Penetrating Radar (GPR) survey, test pits for ground truthing and seawall repairs. Considering the collateral infrastructure risk, the Esplanade seawall may be considered for further maintenance and upgrade into a coastal levee.

Future strategic assessments of coastal hazards at closed landfills may not need to consider this site following complete waste removal and rehabilitation.

7.9 Holloways

The Holloway closed landfill site was found to be exposed to High coastal risk by **2060**, and CBA shows that the most effective coastal hazard mitigation strategy is maintaining and repairing the site following storm-tide events.

Future waste management strategies would benefit from additional information and studies to manage the risk appropriately. Such investigations should be completed before the next strategic assessment.

The extent of the landfill, including configuration and cells (if any) is not documented. The solid waste extent should be surveyed to manage this site better. This could include a Ground Penetrating Radar (GPR) survey and test pits for ground truthing. Also, the toxicity of the waste and leachate diffusion are not fully understood. Therefore, an investigation should determine how successful the ad-hoc liner is working, and this would require groundwater monitoring and testing.

7.10 Summary

Table 7-1 summarises the proposed investigations, actions and studies in a coherent program.

Table 7-1 Recommendations

Site	Additional investigations			Action (milestone)	Site Study (milestones)
Portsmith				Building coastal resilience (2025)	Building Coastal Hazard Assessment (2024)
				Pond maintenance and fence upgrade (2025)	Planning and design for maintenance and upgrade (2024)
					Coastal Protection Feasibility Study (2028)
					Strategic Assessment update (2035)
Yorkey Knob				Erosion protection of embankment (2024)	Planning and design for embankment protection (2024)
					Strategic Assessment update (2035)
Machans				Erosion protection of embankment (2027)	Planning and design for embankment protection (2026)
					Strategic Assessment update (2035)
White Rock				Maintain and upgrade assets (2032)	Planning and design for embankment protection (2025)
					Strategic Assessment update (2035)
Endeavour	2032	2027-2032	2027-2032	Monitoring	Strategic Assessment update (2035)
Aeroglen	2032			Monitoring	Strategic Assessment update (2035)
Mann Street	2024	2024-2028	2024-2028	Monitoring	Strategic Assessment update (2035)
Barlow Park		2024-2028	2024-2028	Monitoring	Strategic Assessment update (2035)
Esplanade	2024			Remove all waste (2025)	Waste removal investigations (2024)
					Seawall upgrade works feasibility study (2024)
Holloway	2027	2027-2032	2027-2032	Monitoring	Strategic Assessment update (2035)

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APPENDIX A
COASTAL CLOSED LANDFILL LITERATURE REVIEW SUMMARY

Appendix A Background

Many landfill sites have been impacted by coastal hazards around the world. In the United States Hurricane Harvey of 2017 led to 13 toxic waste facilities flooded by the event. In 2019, the Fox River in New Zealand caused flooding of a closed landfill site, resulting in extensive amount of solid waste being washed out to sea.

A-1 Risk/type of damage

Damage to landfill sites can be of environmental or structural nature. Environmental impacts are the release of leachate and solid waste dispersal in the environment. Structural damage refers to the damage of seawalls, bund walls, pumps, drainage system, cap, on site buildings etc. Structural damage occurs typically prior to environmental damage.

A-1-1 Environmental

The impact of leachate release depends on the nature of the waste the set-up and exposure of the landfill site. The presence of organic and inorganic contaminants has the potential to significantly impact on the health of marine life (Nicholls, 2021). Older landfills might be constructed without linings which may cause the release of dissolves nitrogen and metals to the surrounding water and sediments.

The ocean-fronting closed landfill site of Allen Harbour in North Kingstown, United States, shown on Figure B-1, is only covered by a riprap seawall and high concentrations of volatile organic compounds (VOC) and semi-VOCs, polycyclic aromatic hydrocarbons (PAHs), pesticides, PCBs and metals were found in the groundwater and soil samples at the landfill site as well as within sediment at distance of 400m south-east from the landfill site. (Agency U. S., 2014)

Figure B-1   Allen Harbour landfill site, Google Earth

Research and guidelines mainly assess the leaching from landfills into freshwater environments, which have shown to increase metal release four to six order of magnitudes (Brand S. O., 2017), but there is limited research into saline environments. The study of Brand published in the peer review journal "Science of the Total Environment" (Brand S. , Will flooding or erosion of historic landfills result in a significant release of soluble contaminants to the coastal zone?, 2020) found an increase of the total metal contents that is released to solution from saltwater inundation. However, the proportion of mobilised metals is very low and dilution in the coastal space is increased compared to most freshwater sites. As such, it was concluded that the erosion of solid waste resulted in a higher impact to ecological health compared to leaching of soluble metals.

A conceptual model of leachate migration for present day and future scenario is shown in Figure B-2, where sea levels increased in the future scenario, resulting in breaching of the defence structure and erosion of solid waste as well as contaminated sediment.

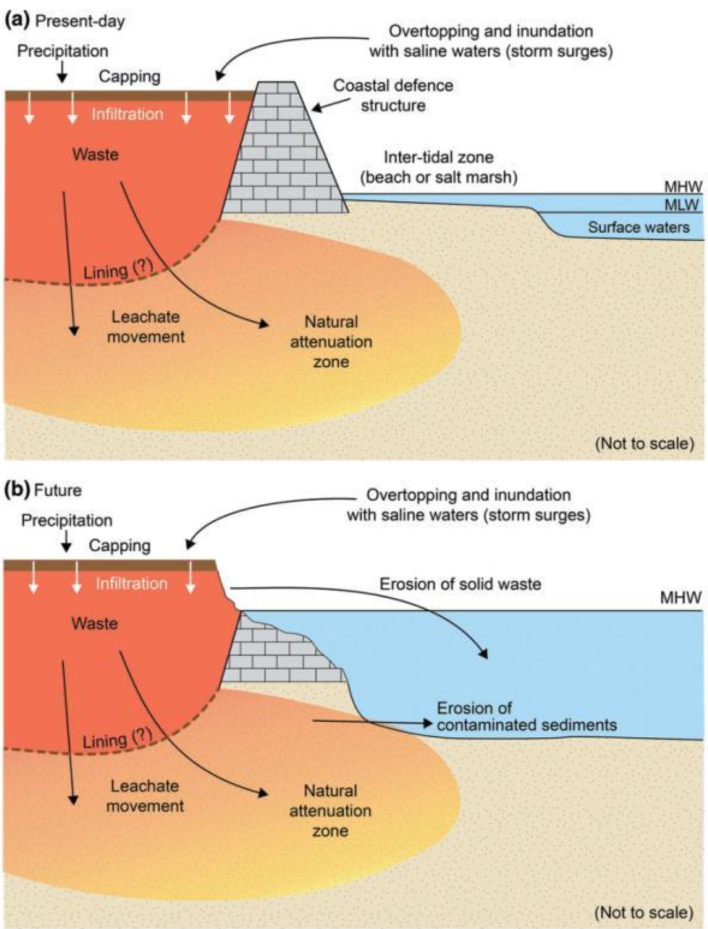

Figure B-2 Conceptual model of leachate migration for present day (a) and future scenario (b) (Brand S. O., 2017)

This study analysed the impacts of saltwater intrusion into landfill sites and made the following conclusions:

- Soluble contaminant release from coastal landfill sites may increase with climate change
- There are high variations in soluble contaminant release between various landfill sites
- Saltwater intrusion increases soluble contaminant release significantly
- Minimal environmental impacts are experienced as a result from the increased leaching; and
- Erosion is assessed to present a greater risk than leaching.

Solid waste release can occur from inundation, especially when waste is uncapped, and erosion as illustrated in Figure B-3. Solid waste can include materials such as asbestos, plastics and composite waste (e.g. batteries). This has the potential to cause physical damage to marine life through entanglement or indigestion. Additionally, beach amenity will be greatly impacted. (Nicholls, 2021) Additionally, where closed landfill sites are used for grazing, there is the potential for toxic metals to translocate to above ground. (Brand S. O., 2017)

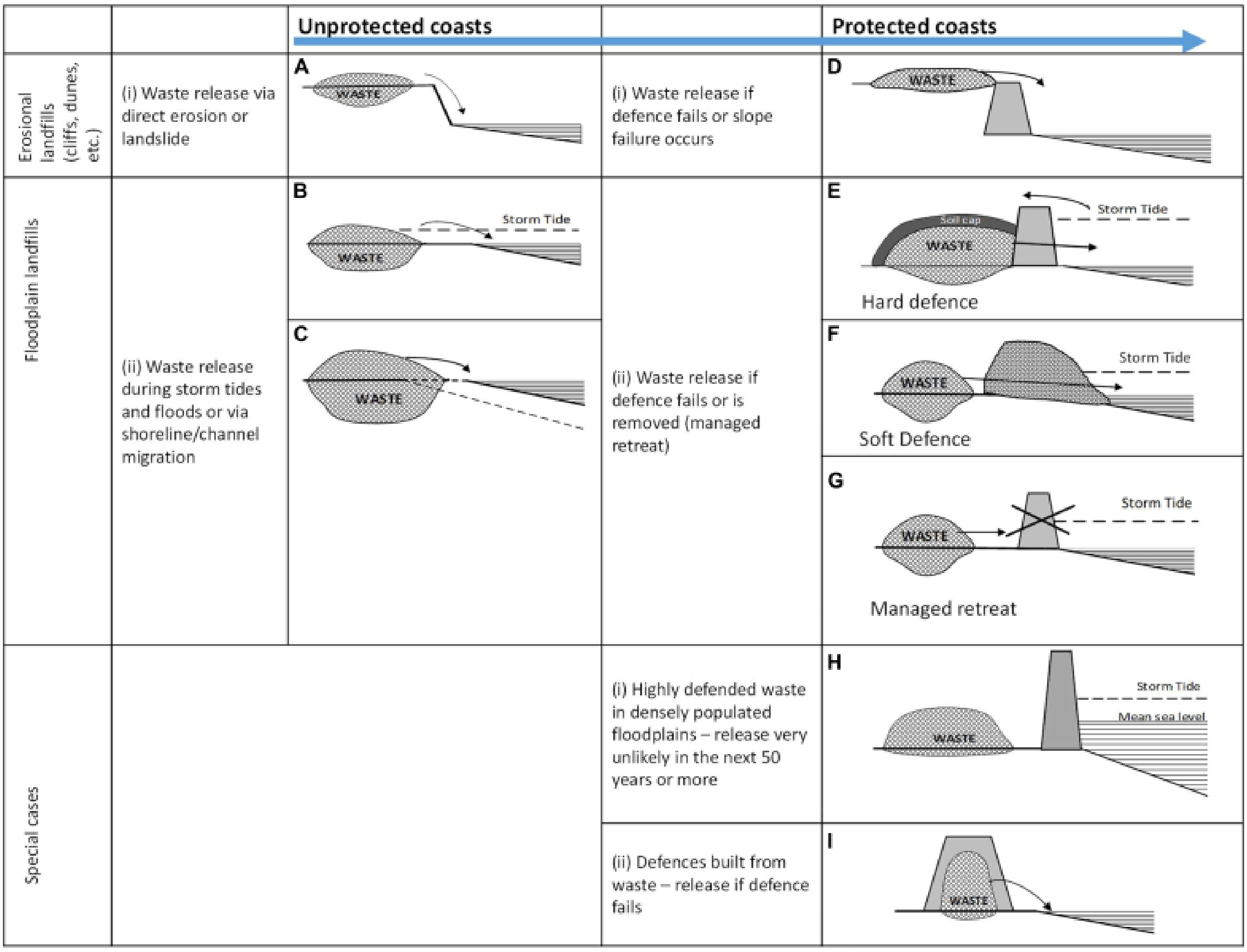

Figure B-3 Solid waste release pathways, (Nicholls, 2021)

A-1-2 Infrastructure

Infrastructure on landfill sites is often located above grade level. As such, damage to infrastructure is generally minor. However, damage to the gas management, storm water control and leachate management facilities as well as damage to parked vehicles can be experienced from flooding events. Damage to the infrastructure located close to the existing grade such as the scale house, maintenance building and blower flare station can also occur.

A-1-3 Examples of damage

Hurricane Harvey in the US caused flooding of 13 toxic waste facilities, resulting in leachate release. However, flood waters were also contaminated from other sources, such as raw sewage, refineries, landfills, septic tanks, medical wastes, feedlots, cemeteries and portable toilets.

Flooding of the Fox River in New Zealand caused erosion of an old landfill site resulting in an estimated amount of 135,000 of kilograms of rubbish washed out to sea. Huge cleanup efforts were undertaken after the event with nearly 1,000 volunteers cleaning up the beaches (Figure B-4). Three years after the event, the landfill site was removed, with rubbish taken to another landfill site, at a cost of $3 million.

An ecological assessment of a Wellington landfill site was undertaken in 2017, showing the impact of leachate on the environment with mutant snails found downstream of the site in 2017 (Figure B-5). However, also other sites in New Zealand are already affected such as the Kaiaua landfill (Figure B-6).

New Zealand rated the urgency of the risk to landfills and contaminated sites as 85 out of 94 – the same as wastewater and stormwater systems. (National Climate Change Risk Assessment for New Zealand, Main report, 2020)

Figure B-4 Cleanup efforts after the Fox River landfill erosion (RNZ, 2022)

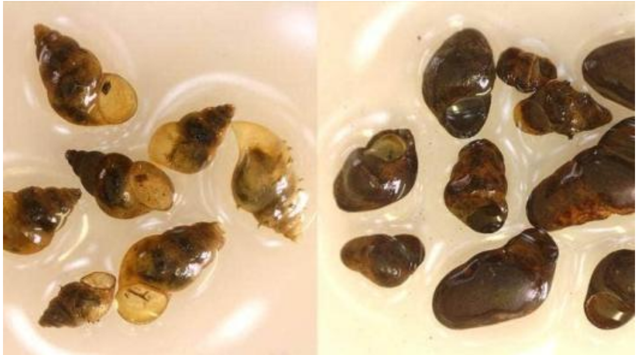

Figure B-5 left: snails upstream of the Wellington landfill site healthy and normal. Right: downstream snails orange and deformed (Macdonals, 2021)

> *"The big lesson from the Fox River response is that it's far easier to prevent and minimise the amount of rubbish we're producing than it is to go and clean it up after it gets washed down rivers. We certainly need to at least understand the extent of the problem and, secondly, what can we do about it? It's never an easy solution."*
>
> *Don Neale – Marine Adviser, Conservation Department*

Figure B-6 Erosion at Kaiaua landfill (Macdonals, 2021)

Several reports from US, Canada, UK, Netherlands show that coastal closed landfill site are vulnerable to coastal hazards. In Australia, the Port Fairy closed landfill site was built on a front dune some 40 years ago and is vulnerable to erosion and release of solid waste as shown on Figure B-7. Water Technology carried out several studies and designed a temporary rock structure to reduce the erosion risk in 2019.

Figure B-7 Port Fairy landfill erosion (ABC News, 2019)

Solid waste can be transported across vast distance by coastal and oceanic currents, with reports of significant amounts of solid waste being washed up on Australian northern beaches originating from Asia.

A-2 Remediation and treatment works

The previously mentioned example of Allen Harbour was treated to limit environmental impacts. The main concerns were leachate, erosion of the landfill face and stormwater runoff. Treatment of the site included:

- Multimedia cap to reduce stormwater runoff, erosion and infiltration.
- Riprap seawall to reduce erosion from tides and storm surges; and
- Restoration of 1.5 acres of intertidal wetlands.

The works were completed in 1999 and are performing satisfactory since then. The town of North Kingston who owns the site is planning on using it for open space/passive recreation in the future. (Agency U. S., 2014) However, it seems that no consideration of climate change was included in the study and the selection of remedial options. While the cap was constructed above the 100-year flood level, increased inundation is to be expected with sea level rise. It is uncertain if and how the remedial works will perform in the long term in limiting environmental damage.

Another example is at Nelson Lagoon, Alaska, a very remote site where the landfill is located on a sandspit. There are no other suitable landfill sites in the vicinity to accommodate waste removal of Nelson Lagoon Village Council. Partial waste treatment is recommended to recycle metals, propane tanks and lead-acid batteries, with the remainder of toxic waste to be disposed off-site. Waste minimisation is also recommended to reduce the amount of waste going to the landfill site in the future. Monitoring of erosion rates is to be undertaken by the community. Further research into suitable mitigation measures is recommended (Conservation, 2015). As such, a long-term strategy for the site is still outstanding and it is unclear which action is to be applied should erosion of waste occur.

Historically, treatment options mostly involved around protection or removal of the landfill site (Nicholls, 2021). Due to the costs of protection and removal options, there was often a need to explore further options that provide sufficient environmental protection while also being cost effective.

Treatment options differ, depending on the landfill site setup (e.g. is the site lined and capped?), volume and waste composition as well as the site exposure to saltwater inundation and/or erosion, current-day and with climate change impacts. If solid waste loss is considered the main issue at a site, other treatment options might apply compared to sites where leachate seepage is of greater concern.

Adjacent land use can also impact on the most appropriate treatment option. For example, is the landfill site is along a stretch of coastline that is already highly modified and protected, protection of the landfill site might also be appropriate. If however, the landfill site is located in an isolated area with no other significant infrastructure around, protection might not be the most viable option. Shielding of surrounding areas of high environmental significance will also need to be considered and the avoidance of disturbance might be more relevant.

A-3 Risk assessment methodology

Risk is typically considered as a function of the probability of an adverse event happening, magnified by its consequences. There are many factors that may influence the probability that contaminated materials from historic coastal landfill sites are released, including wave exposure, the condition and design standard of any flood defences present, and local coastal erosion rates (Alaska Department of Environmental Conservation 2015)

The consequences of pollution occurring are dependent on the vulnerability of the receptors (Wamsley 2015), which can be considered as the probability that the receptors will be affected by hazards or drivers and is often considered in terms of a dose–response relationship (Gormley et al. 2011). Therefore, the consequences of contaminated materials being released will depend upon the quantity of materials released and their contaminant loads, contaminant bioavailability and mobility, dilution by the receiving waters, and receptor sensitivity to those contaminants. In turn, the quantity of materials released will depend on many of the same factors as the probability of contaminated material release, and the size of the landfill (i.e., quantity of waste), whether it is divided into structurally stable cells, the mechanical properties of the waste (e.g., waste cohesion), the shape of the landfill (i.e., the proportion of it adjacent to the coast), and how quickly any breach can be repaired (Cooper et al. 2013; Alaska Department of Environmental Conservation 2015) (Brand S. , Risk screening assessment for ranking historic coastal landfills by pollution risk, 2018)

Index and indicator methods have been found to miss important data, can be biased and complicated and further site work is usually recommended following coastal landfill vulnerability studies.

APPENDIX B
COASTAL INUNDATION MAPPING

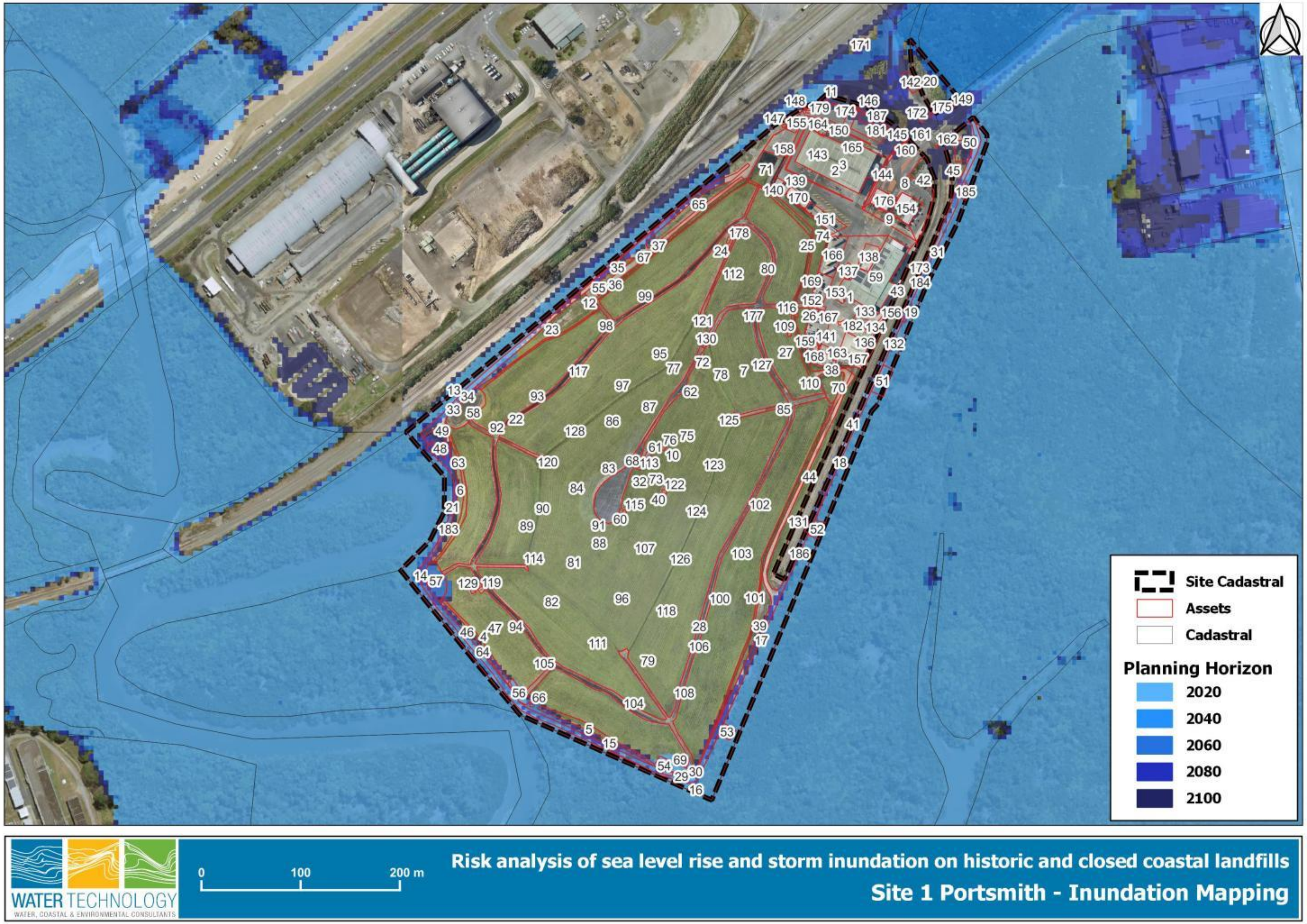

Figure C-1 Portsmith Site – Coastal Inundation

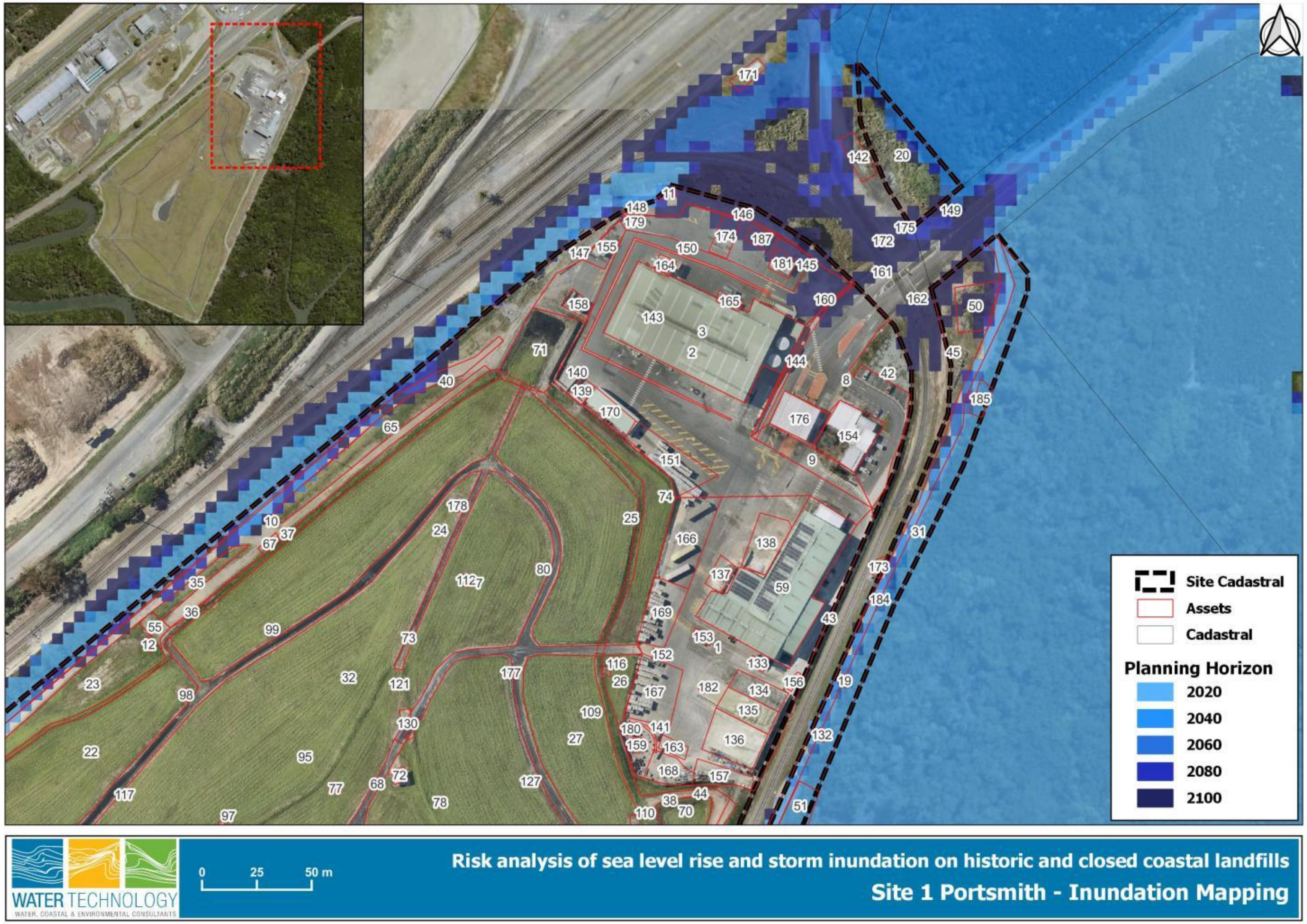

Figure C-2 Portsmith Site - Coastal Inundation – detail

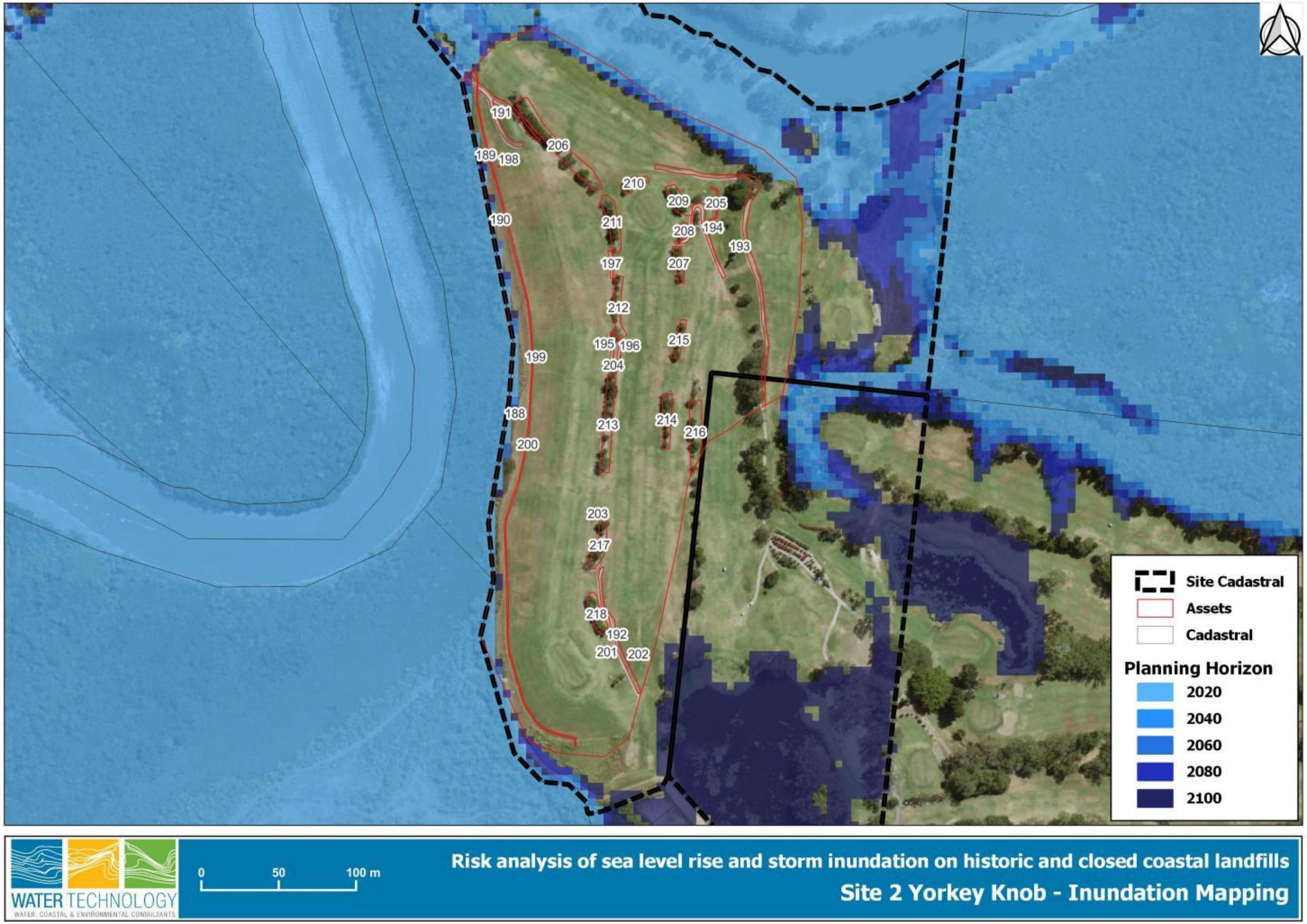

Figure C-3 Yorkeys Knob Site – Coastal Inundation

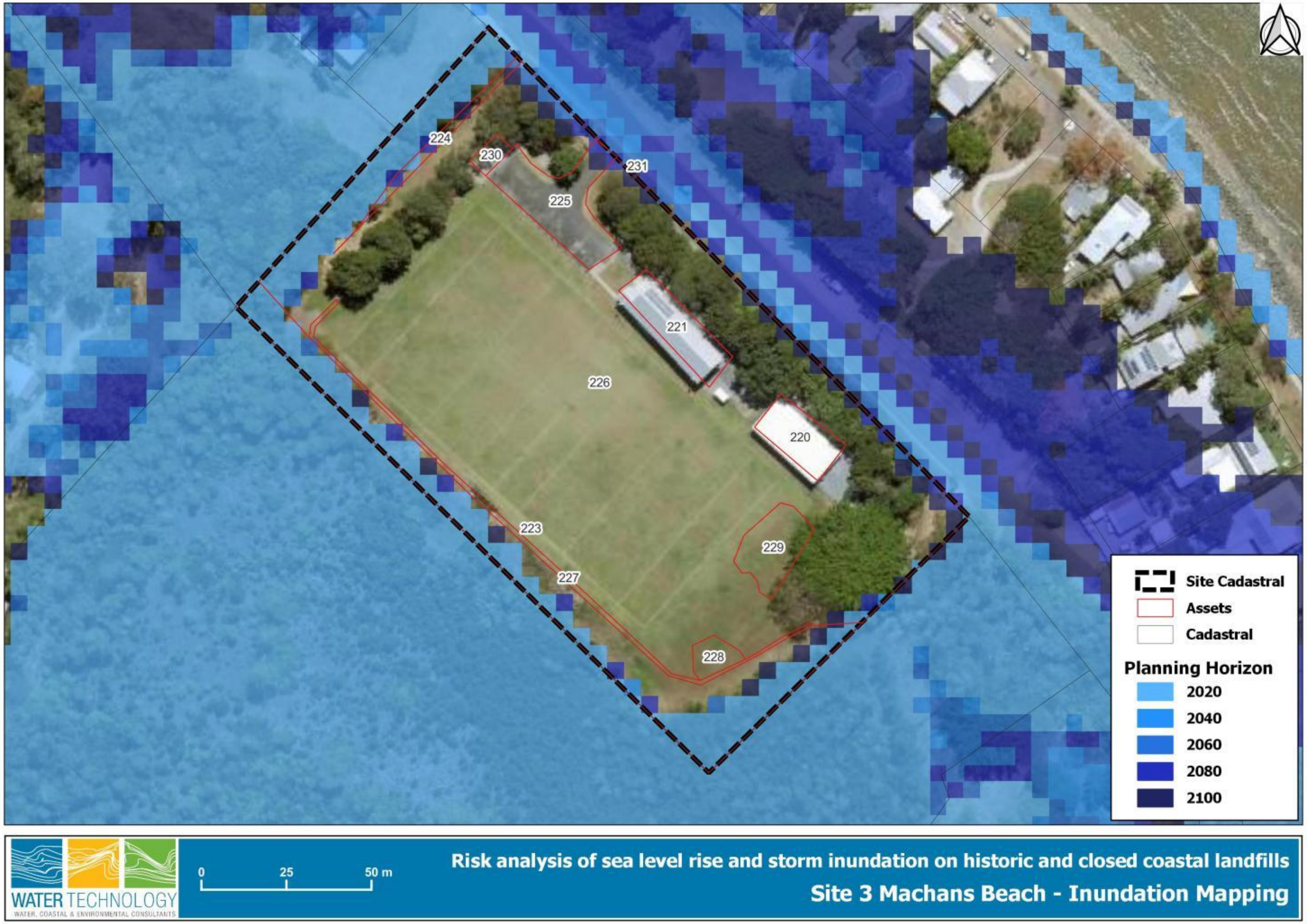

Figure C-4 Machan Site – Coastal Inundation

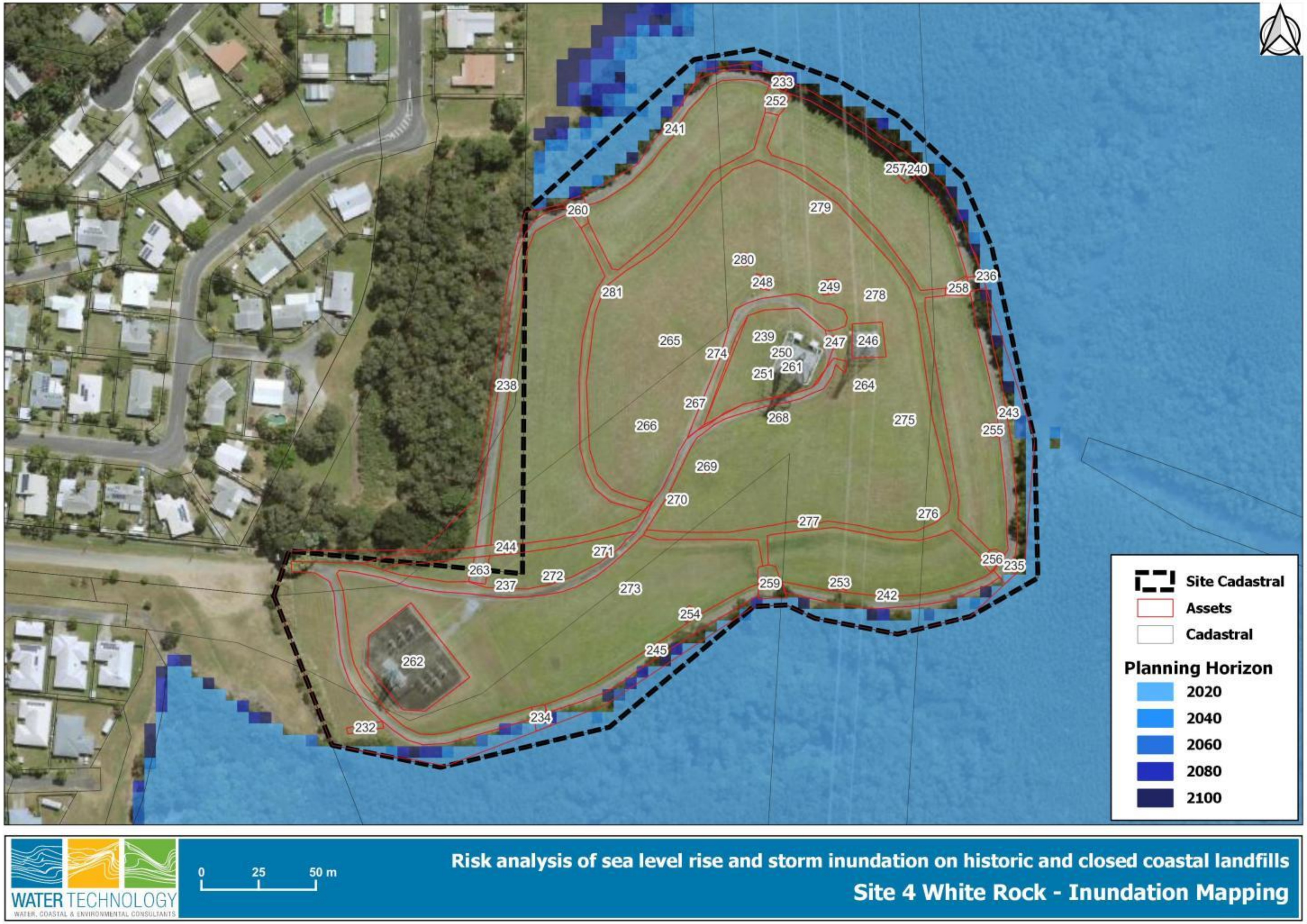

Figure C-5 White Rock Site – Coastal Inundation

Figure C-6 Endeavour Site – Coastal Inundation

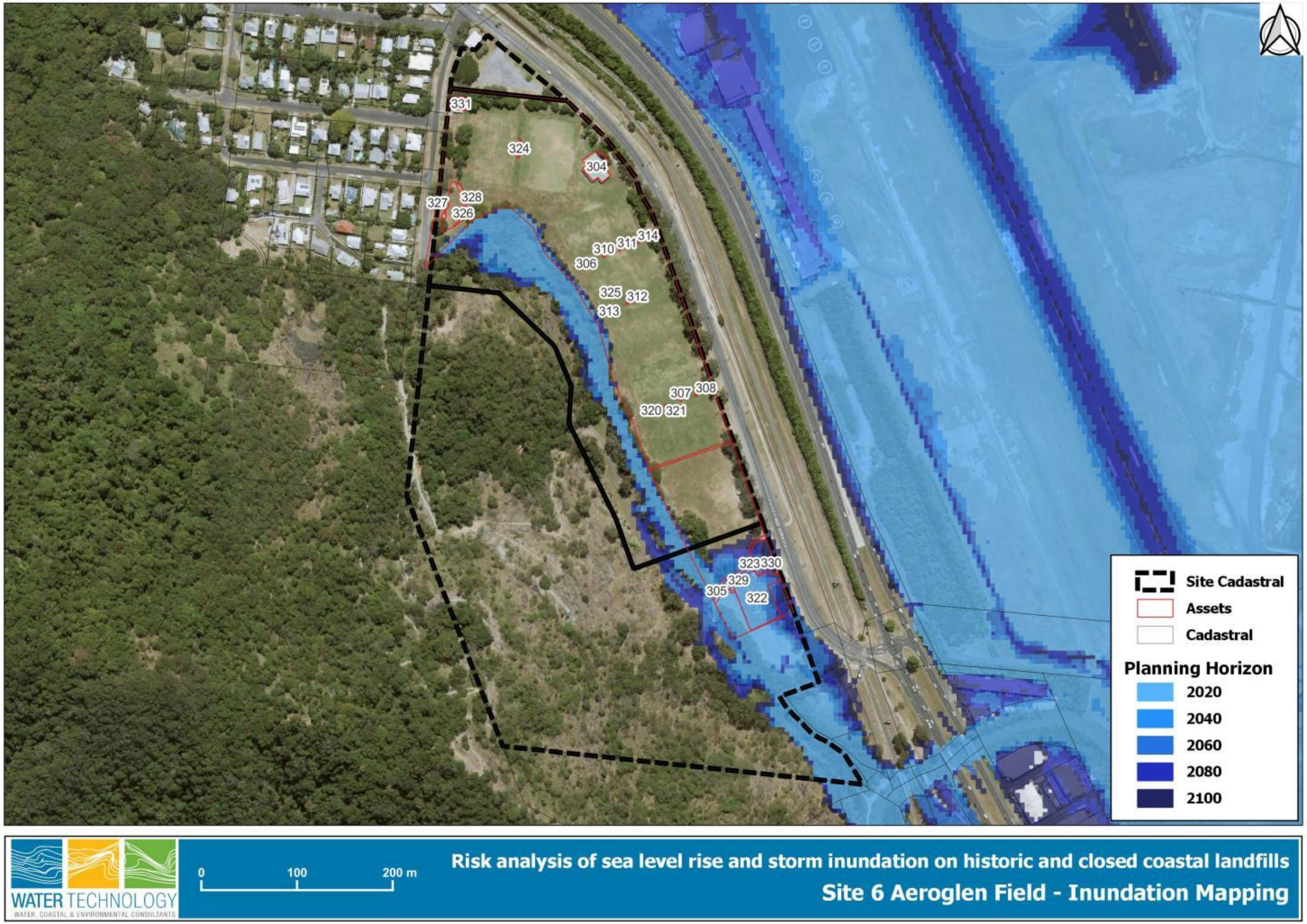

Figure C-7 Aeroglen Site – Coastal Inundation

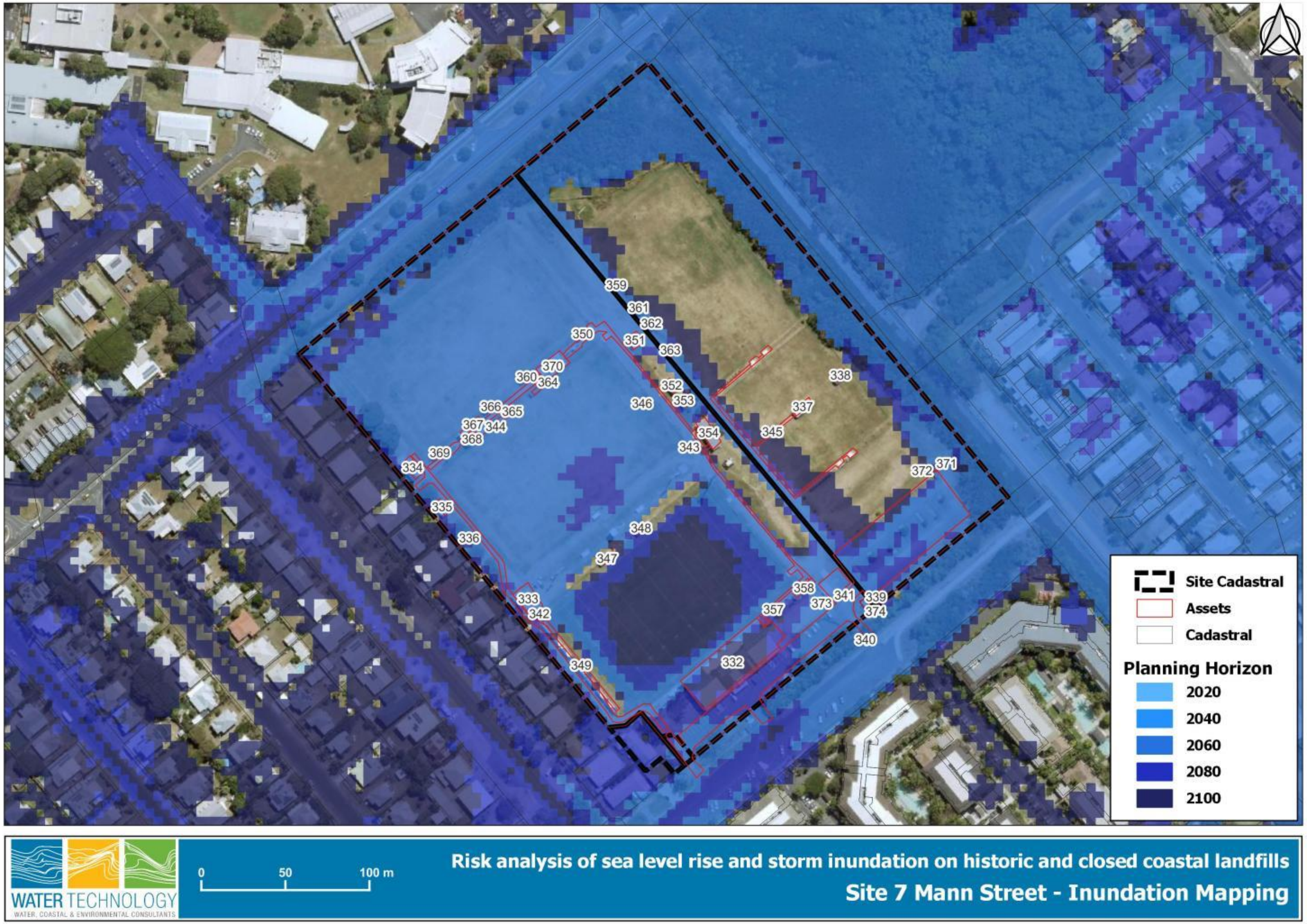

Figure C-8 Mann Street Site – Coastal Inundation

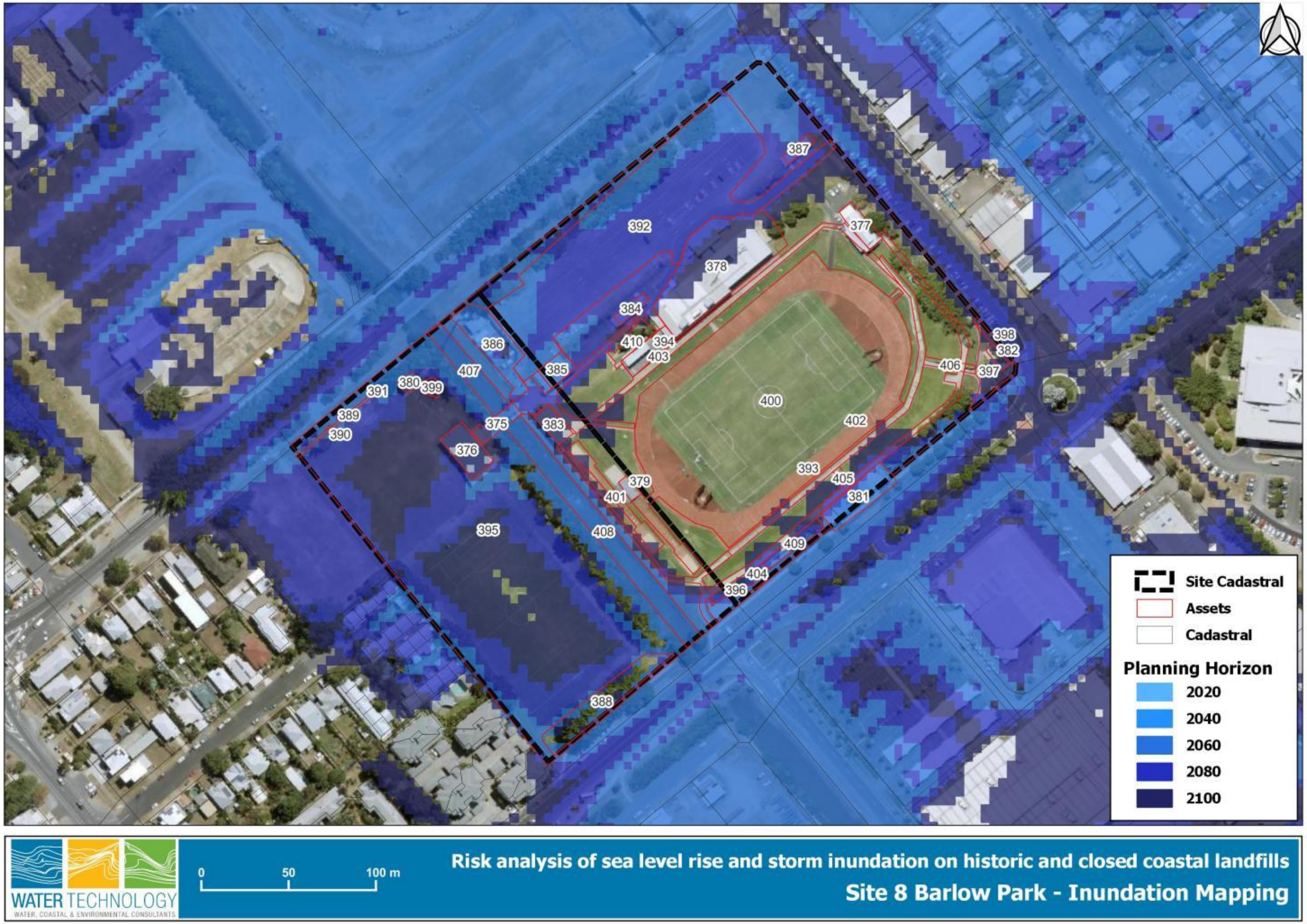

Figure C-9 Barlow Park Site – Coastal Inundation

Figure C-10 Esplanade Site – Coastal Inundation

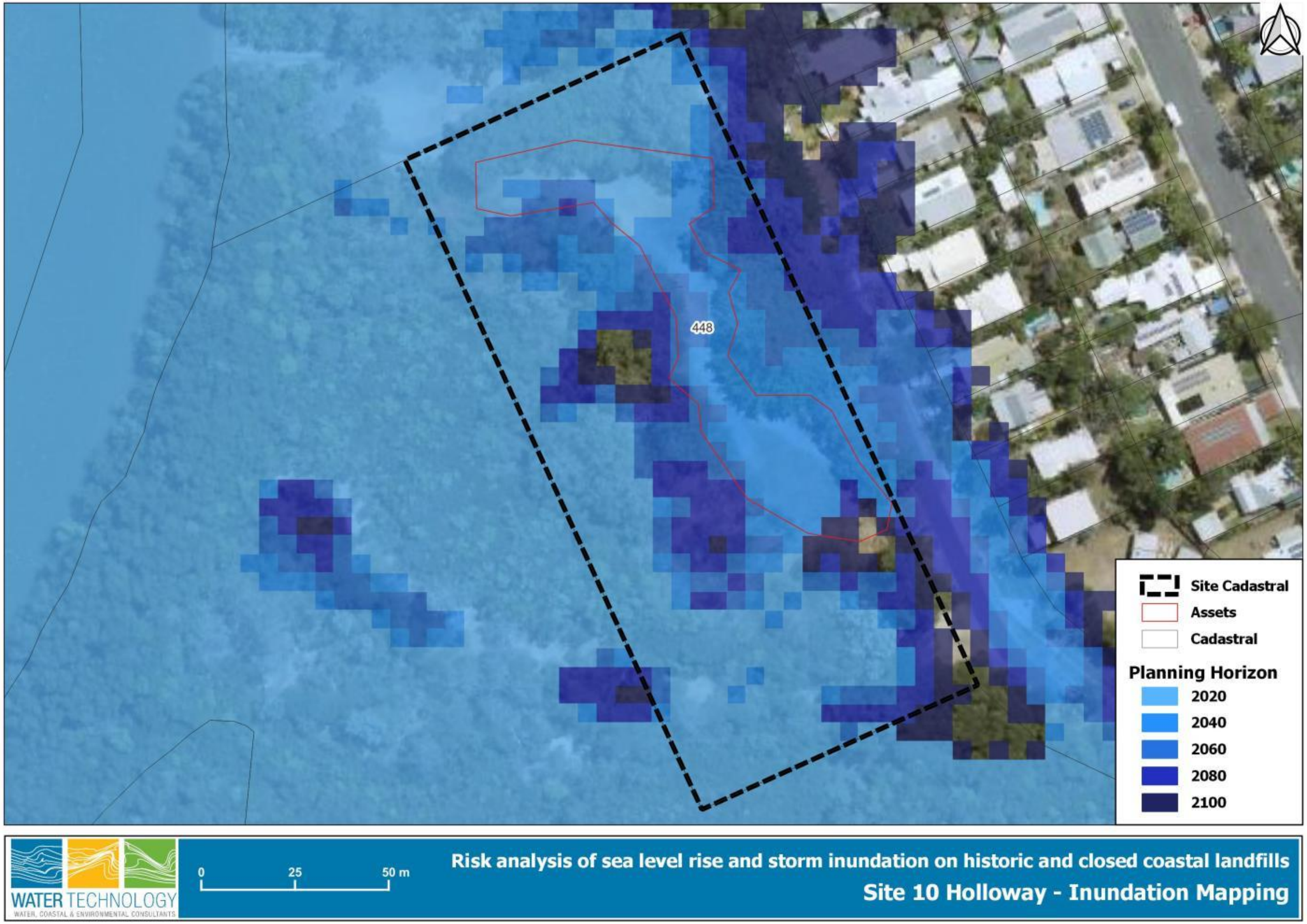

Figure C-11 Holloway Site - Coastal Inundation

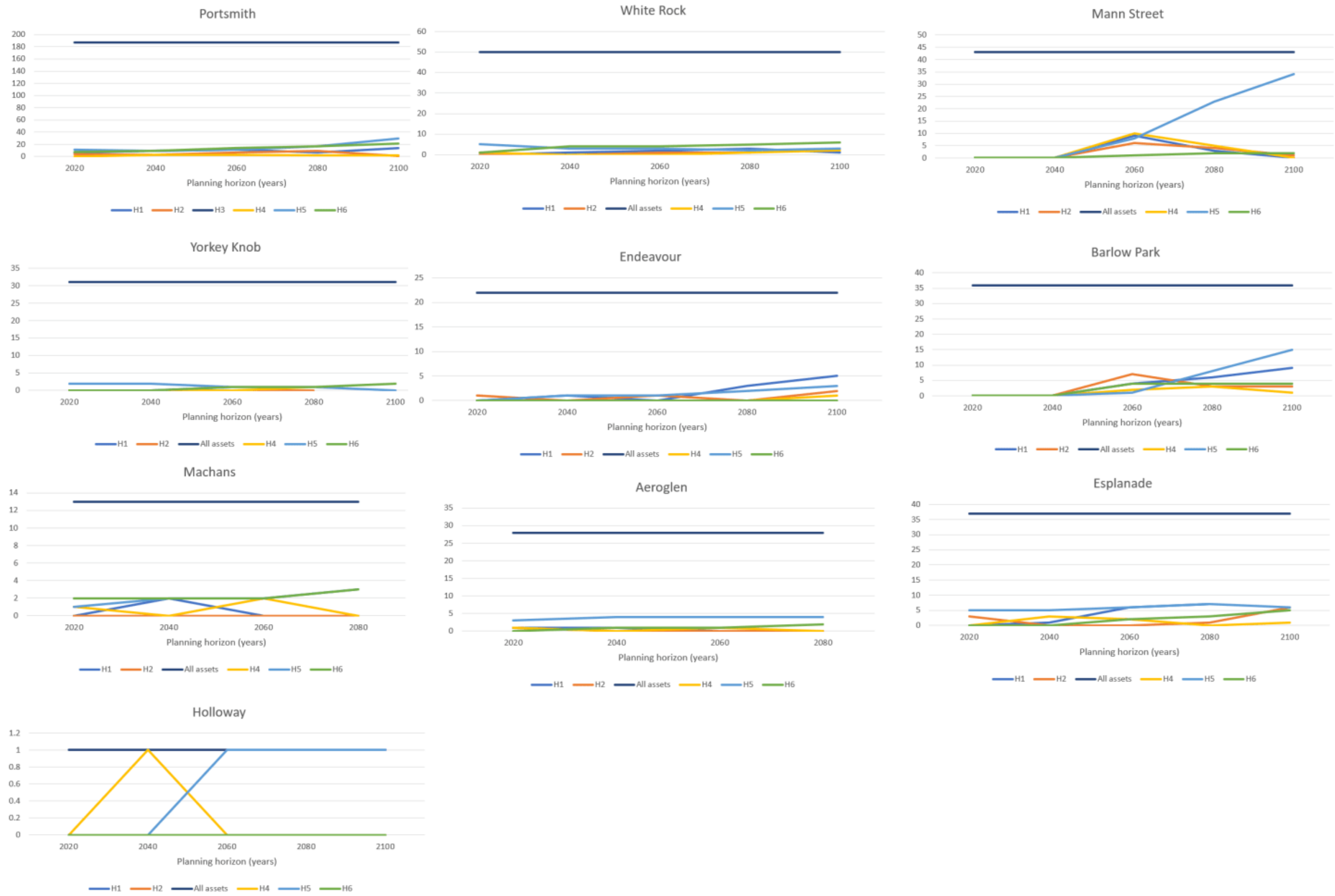

Figure C-12 Projection of inundation vulnerability for closed landfill assets at each site (Hazard Category vs Epoch)

APPENDIX C
COASTAL FLOOD MAPPING

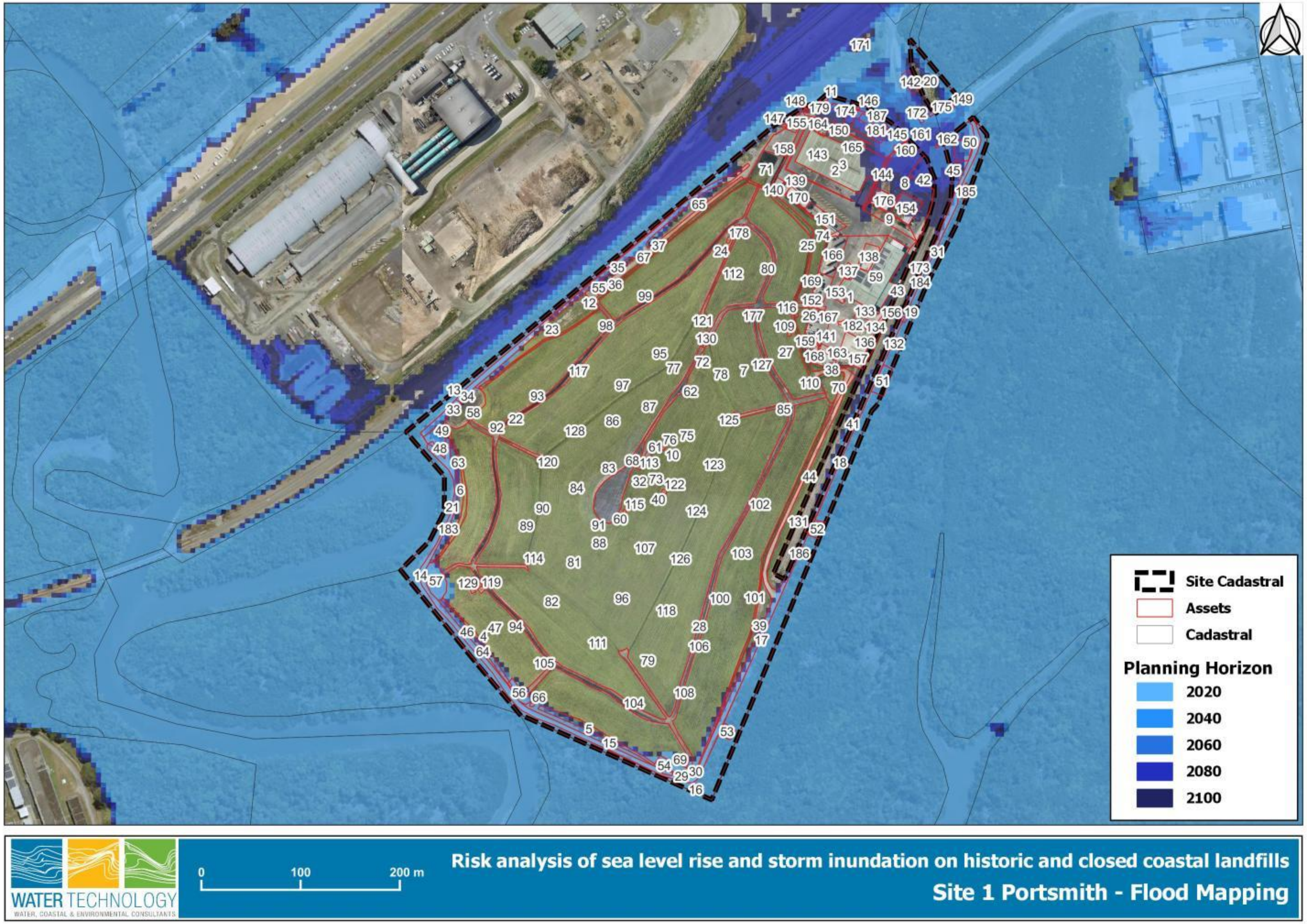

Figure D-1 Portsmith Site - Coastal Flooding

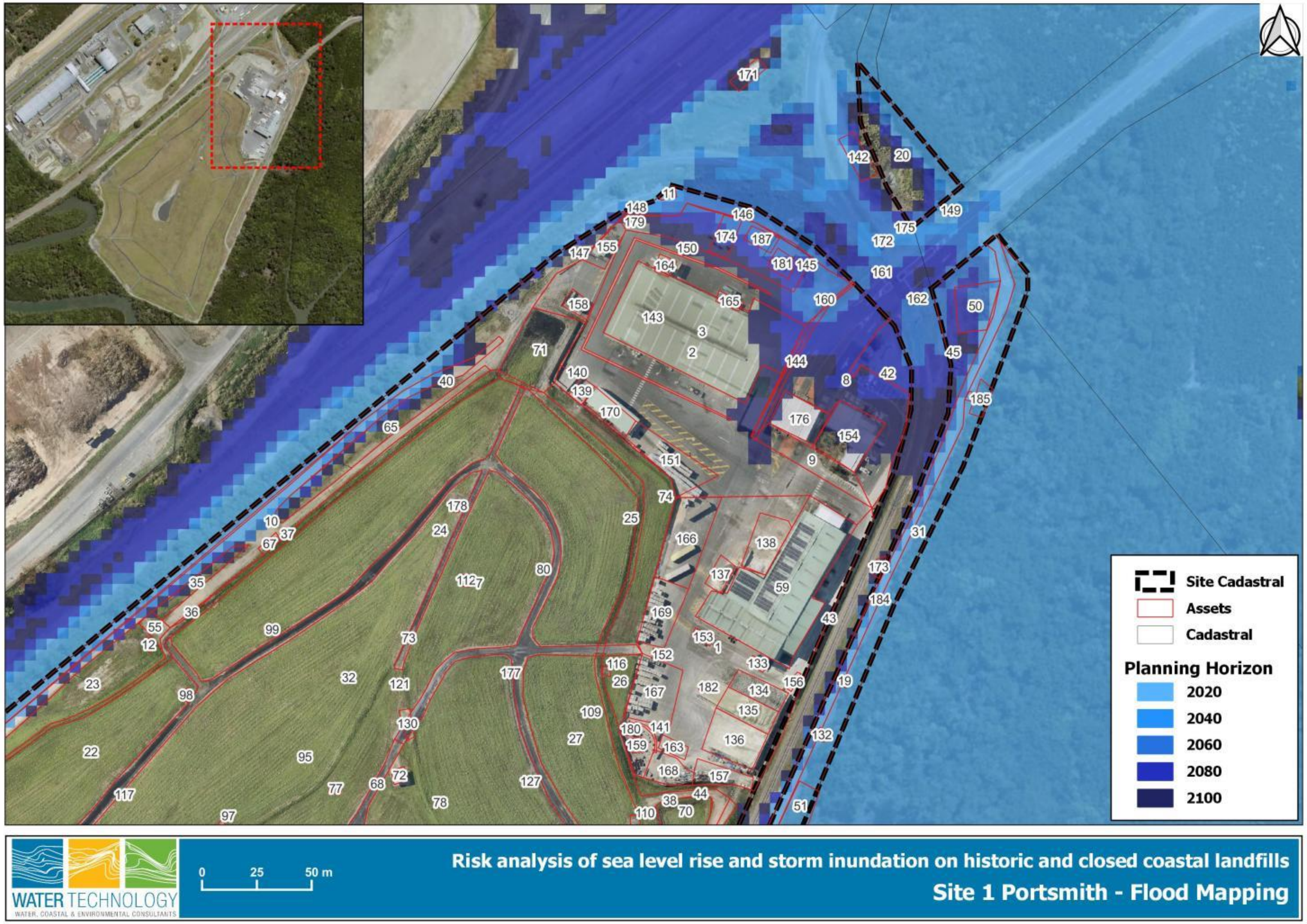

Figure D-2 Portsmith Site – Coastal Flooding - Details

Figure D-3 Yorkeys Knob Site – Coastal Flooding

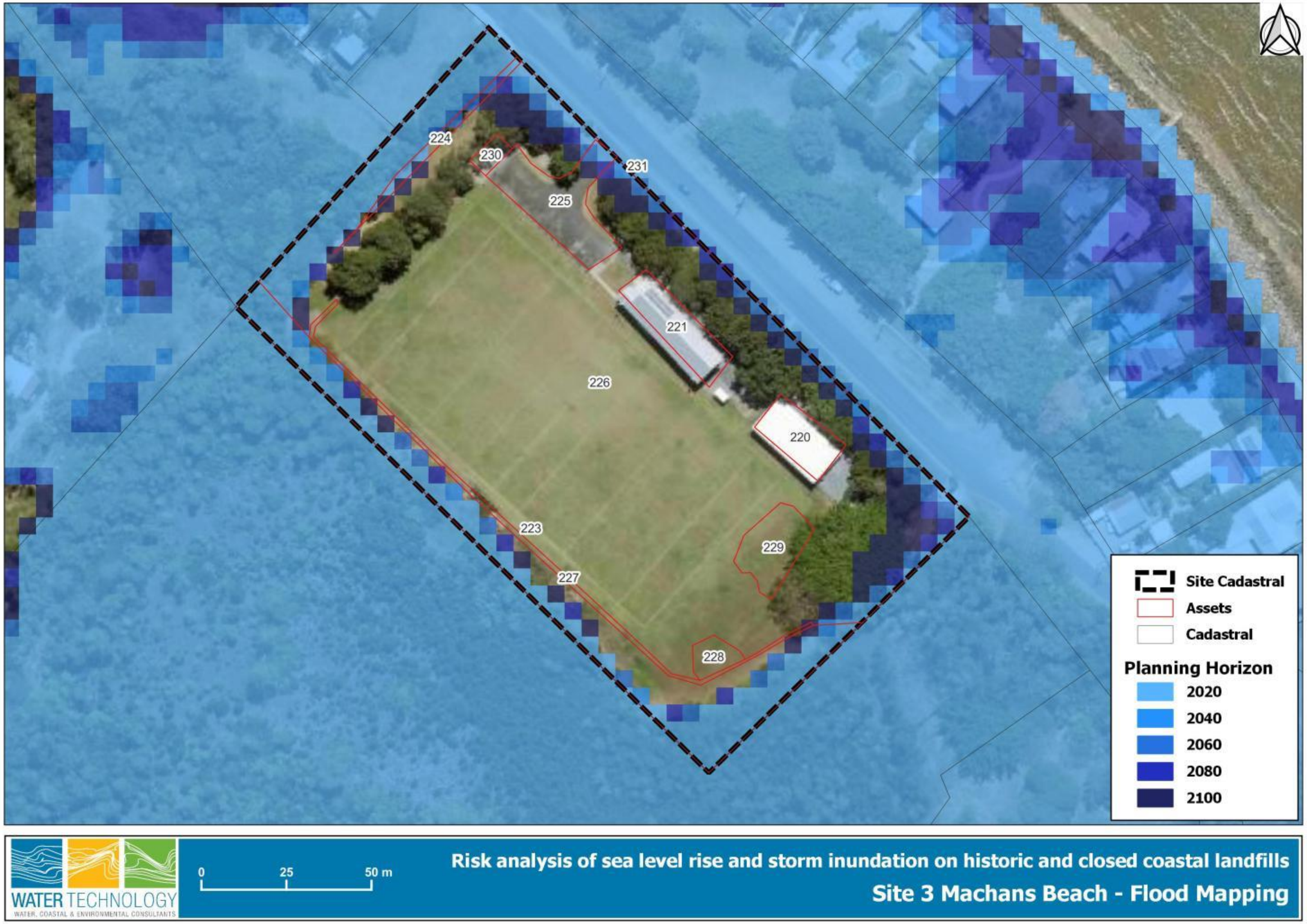

Figure D-4 Machans Site – Coastal Flooding

Figure D-5 White Rock Site – Coastal Flooding

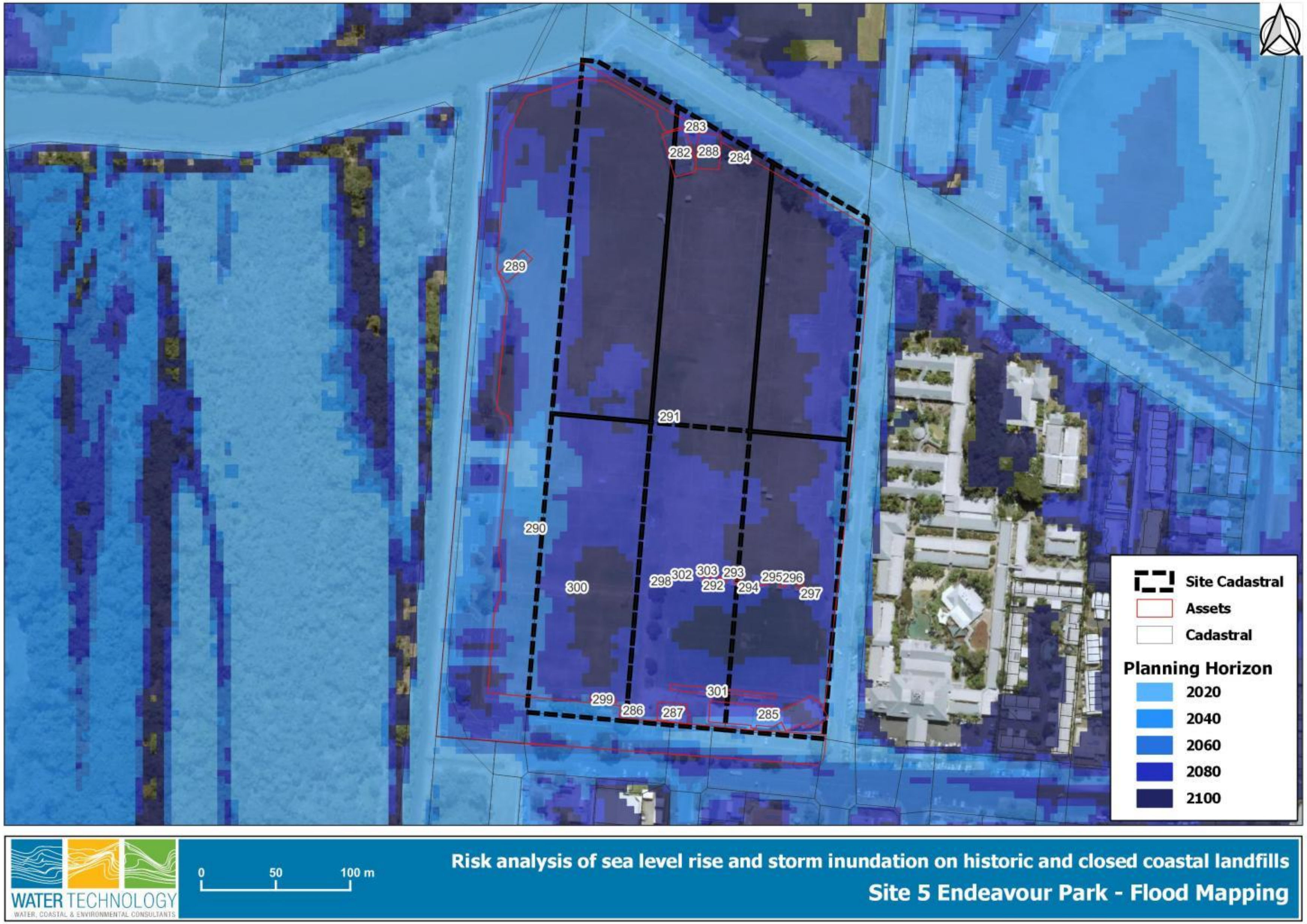

Figure D-6 Endeavour Park – Coastal Flooding

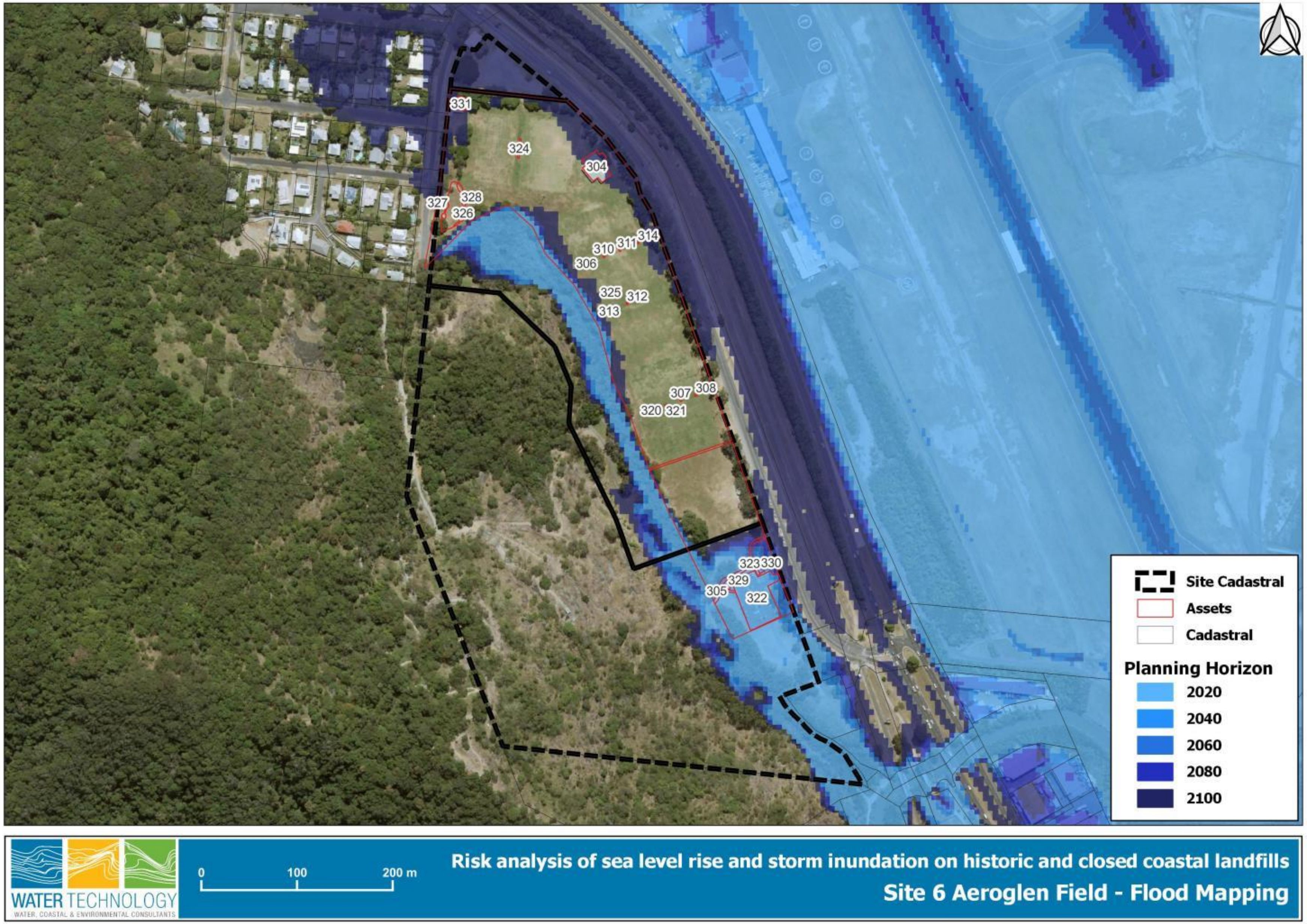

Figure D-7 Aeroglen Site – Coastal Flooding

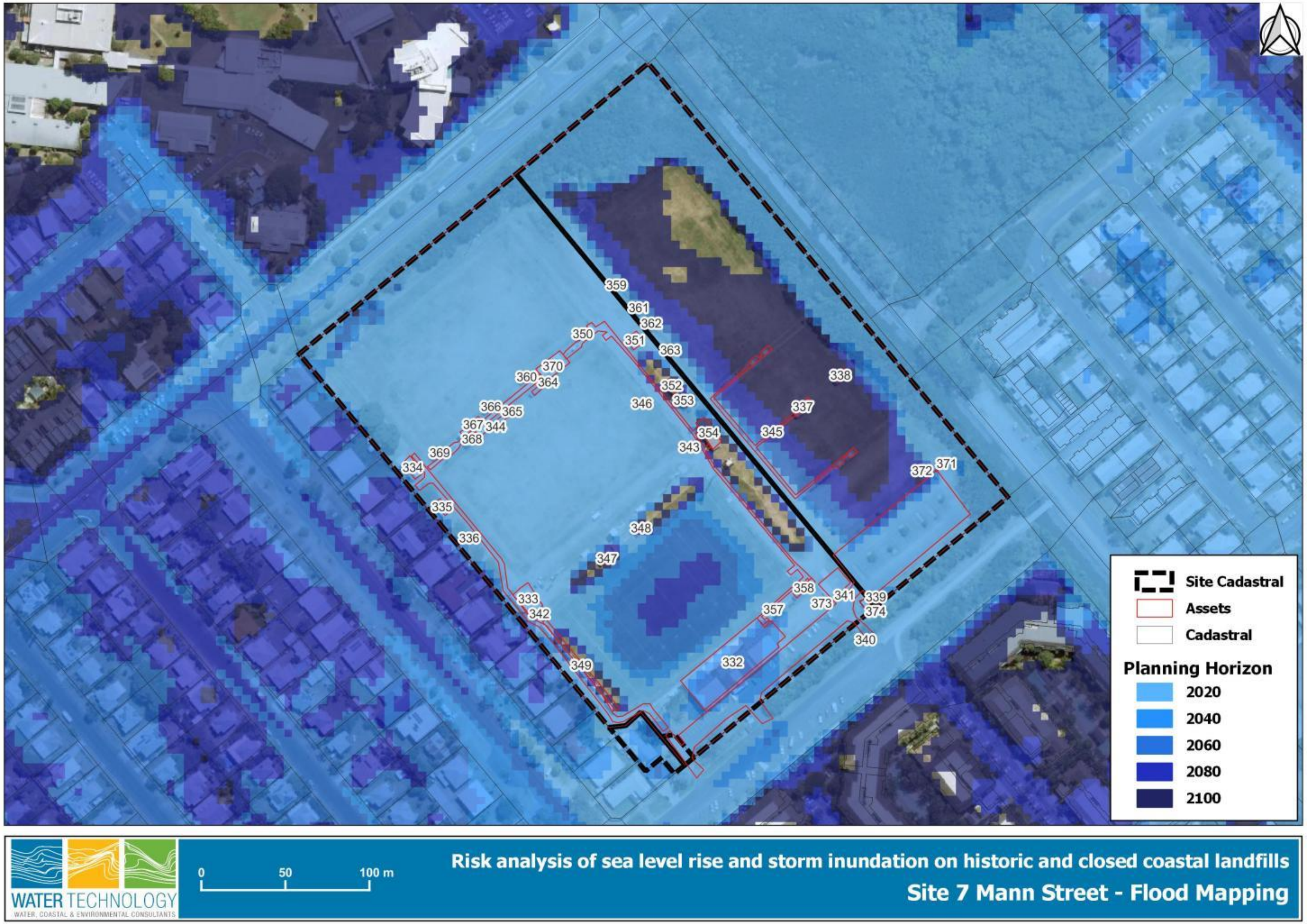

Figure D-8 Mann Street – Coastal Flooding

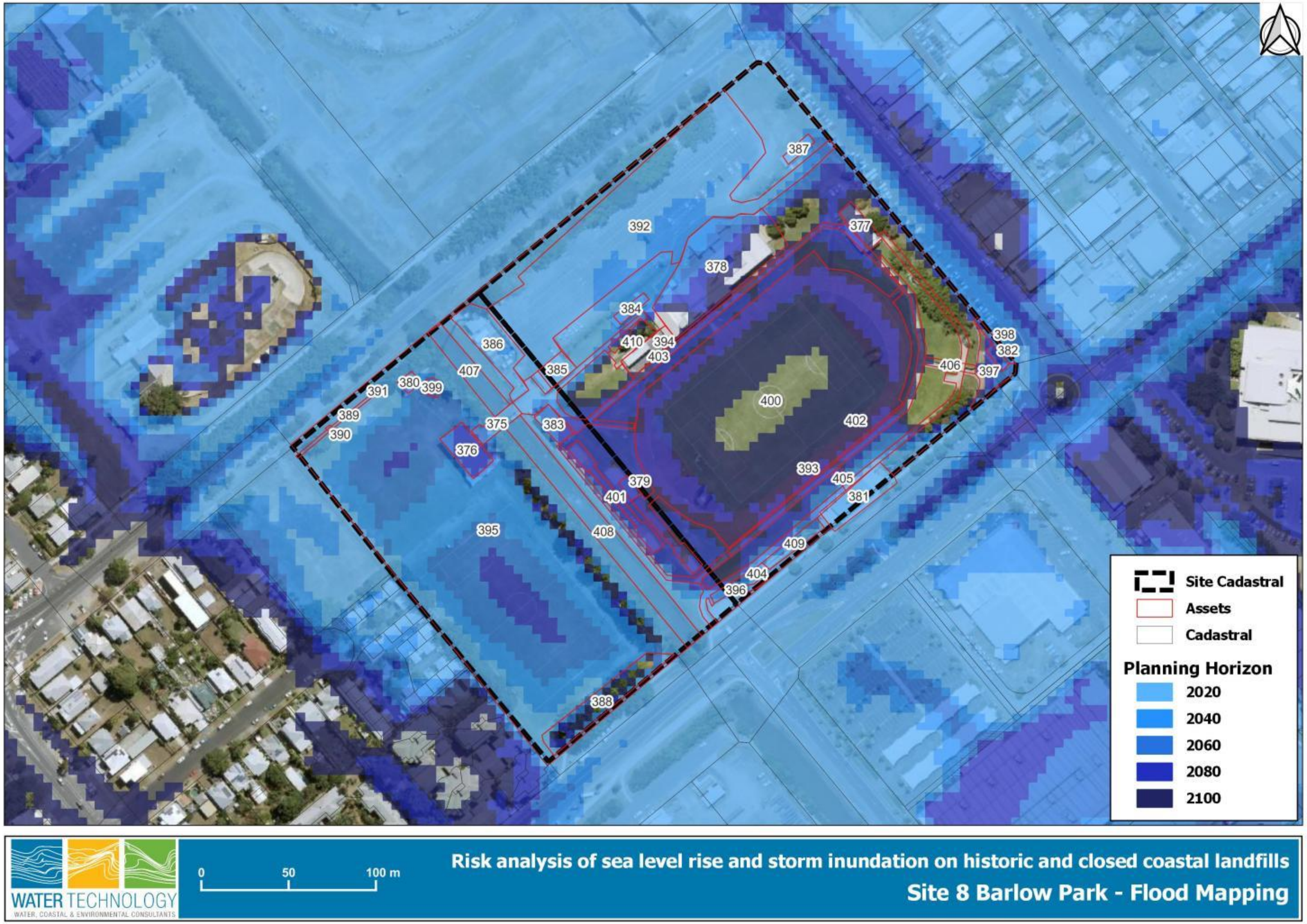

Figure D-9 Barlow Park – Coastal Flooding

Figure D-10 Esplanade Site – Coastal Flooding

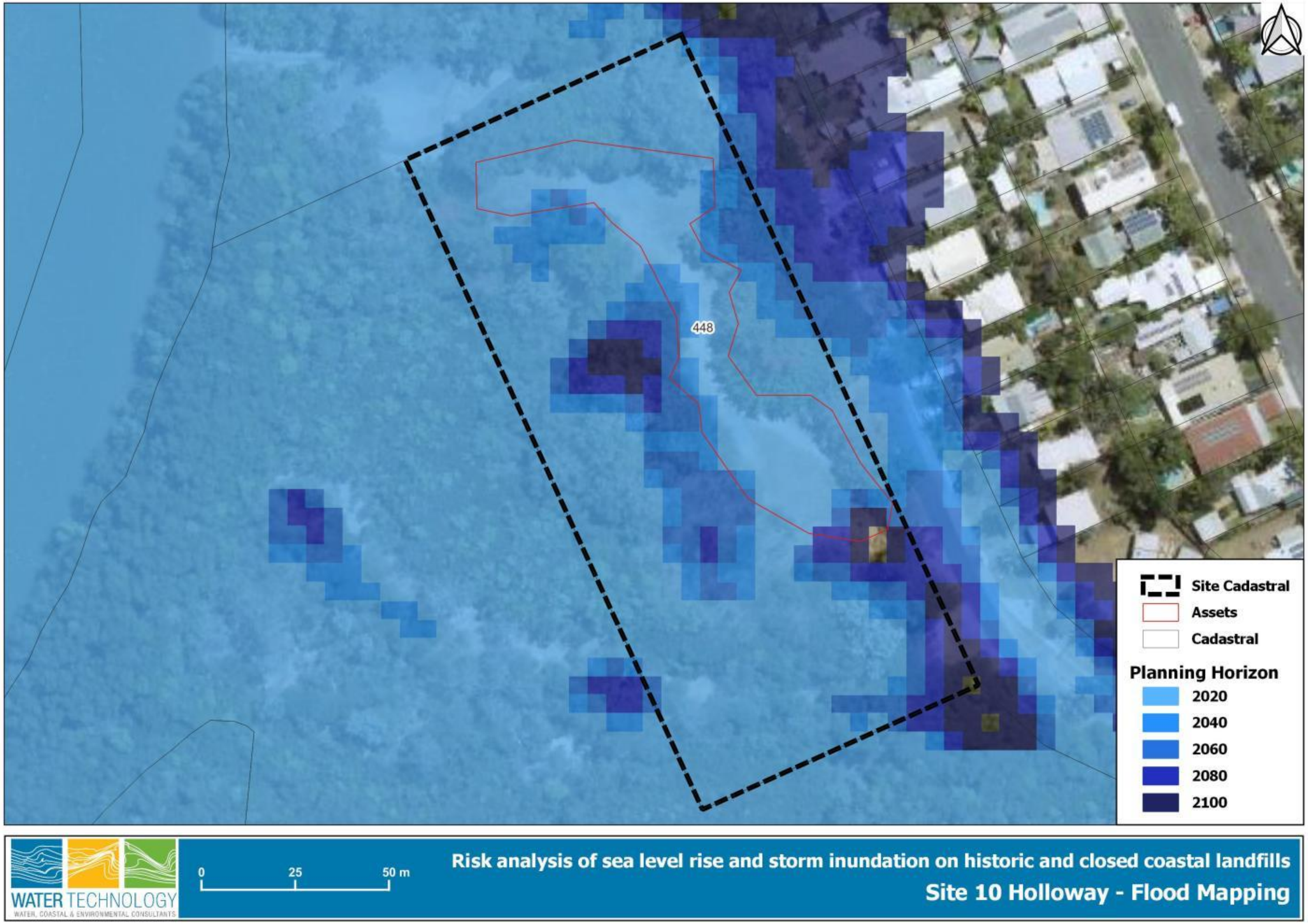

Figure D-11 Holloway Site – Coastal Flooding

Figure D-12 Projection of flooding vulnerability for closed landfill assets at each site (Hazard Category vs Epoch)

APPENDIX D
ASSET SUBMERGENCE

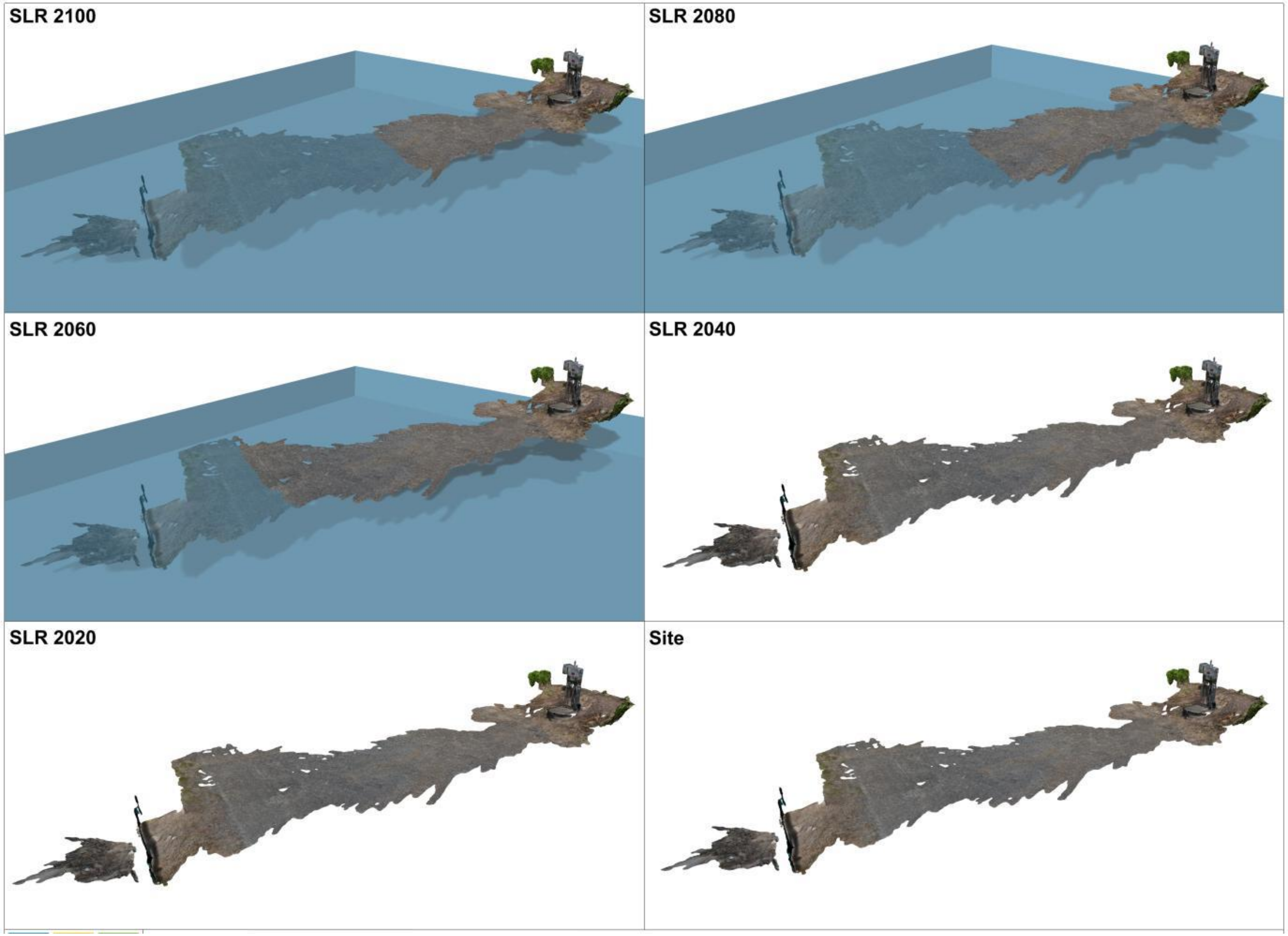

Figure E-1 **Portsmith Site – Gas Well with Groundwater Monitoring 6 – Coastal Inundation – Asset ID16**

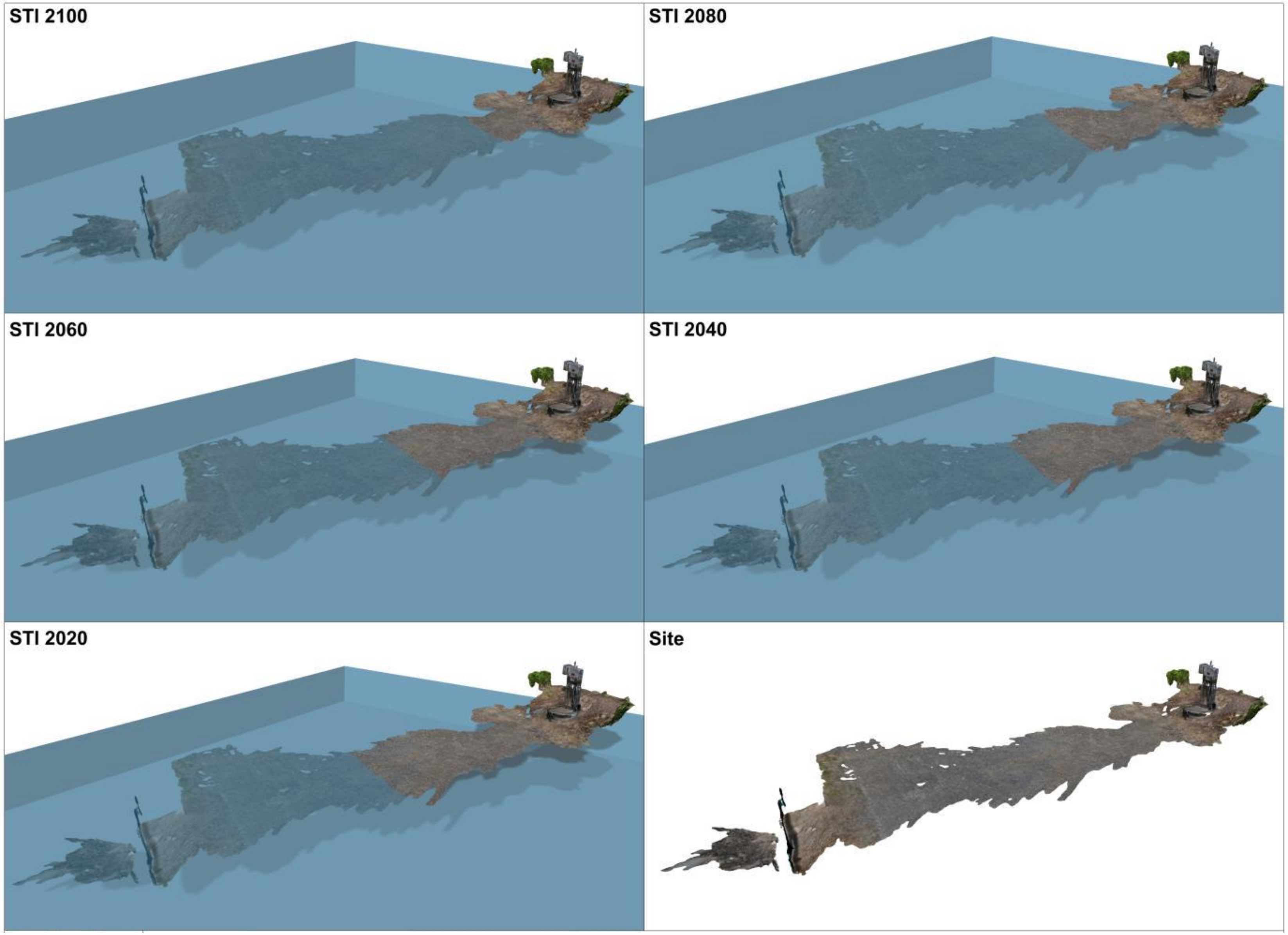

Figure E-2 Portsmith Site – Gas Well with Groundwater Monitoring 6 – Coastal Flooding – Asset ID16

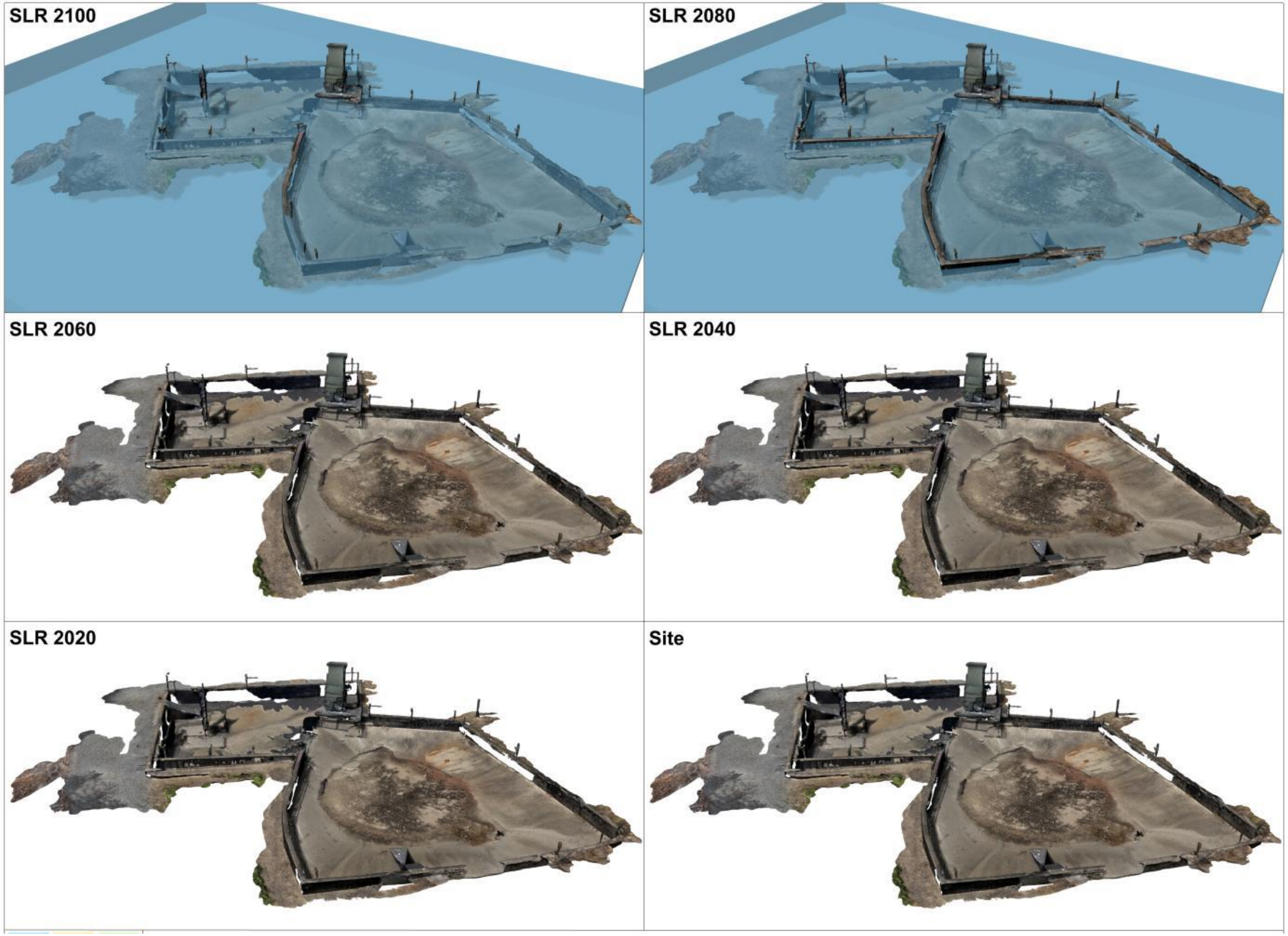

Figure E-3 Portsmith Site – Leachate Pump Well – Coastal Inundation – Asset ID49

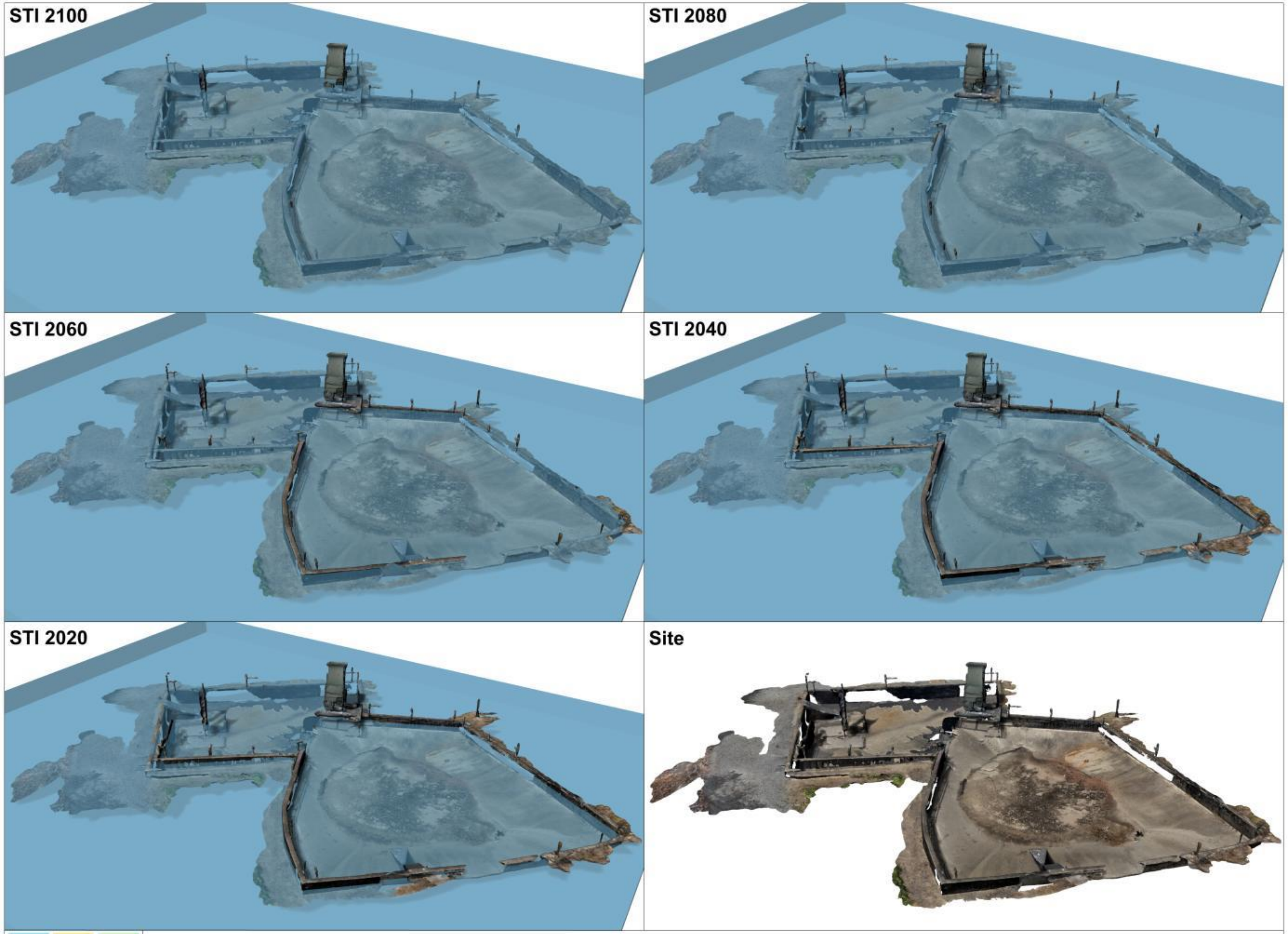

Figure E-4 Portsmith Site – Leachate Pump Well – Coastal Flooding – Asset ID49

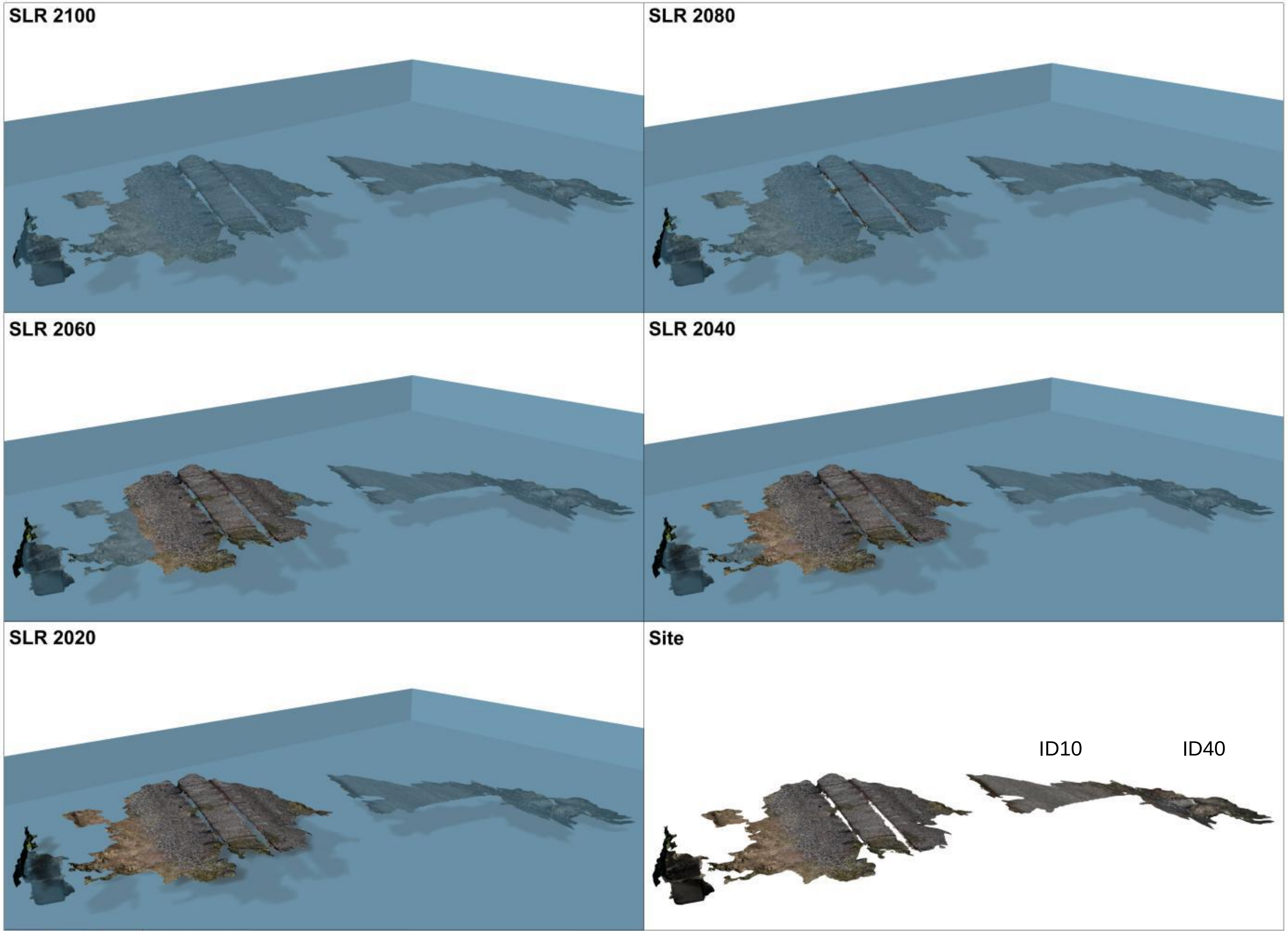

Figure E-5 Portsmith Site – Southern edge – Coastal Inundation – Asset ID10,40

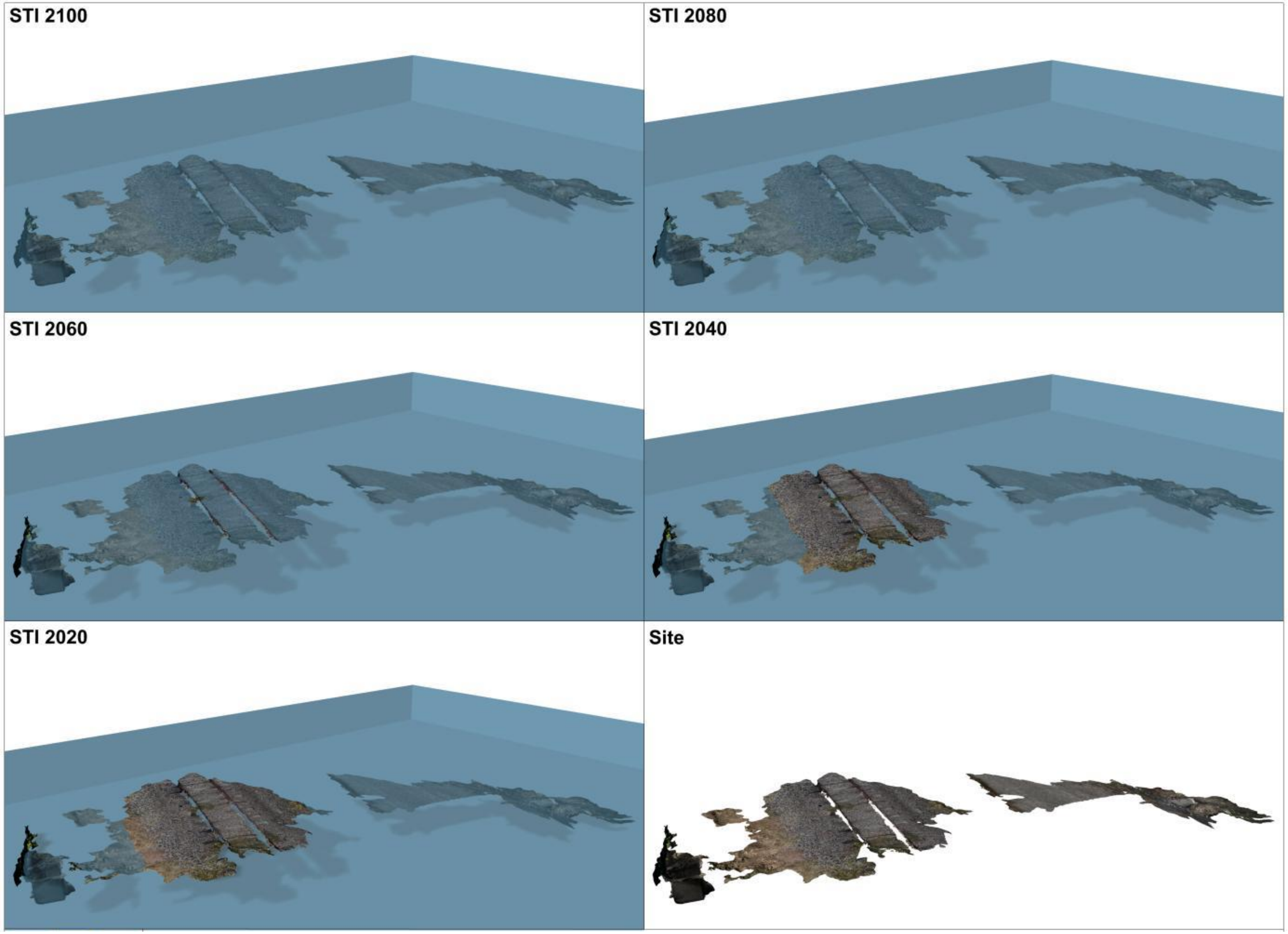

Figure E-6 Portsmith Site – Southern edge – Coastal Flooding – Asset ID10,40

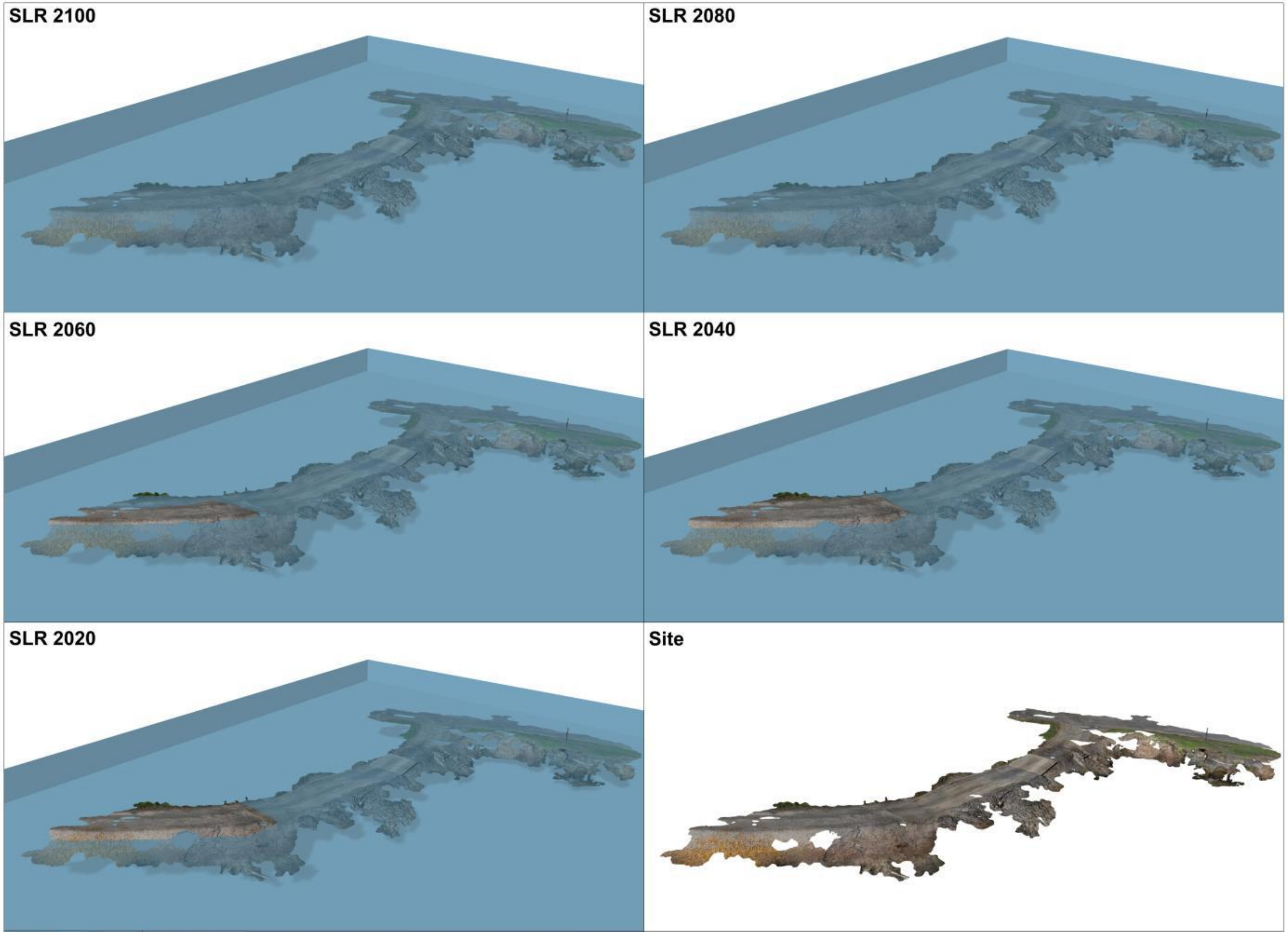

Figure E-7 Portsmith Site – Access Road Entry – Coastal Inundation– Asset ID10

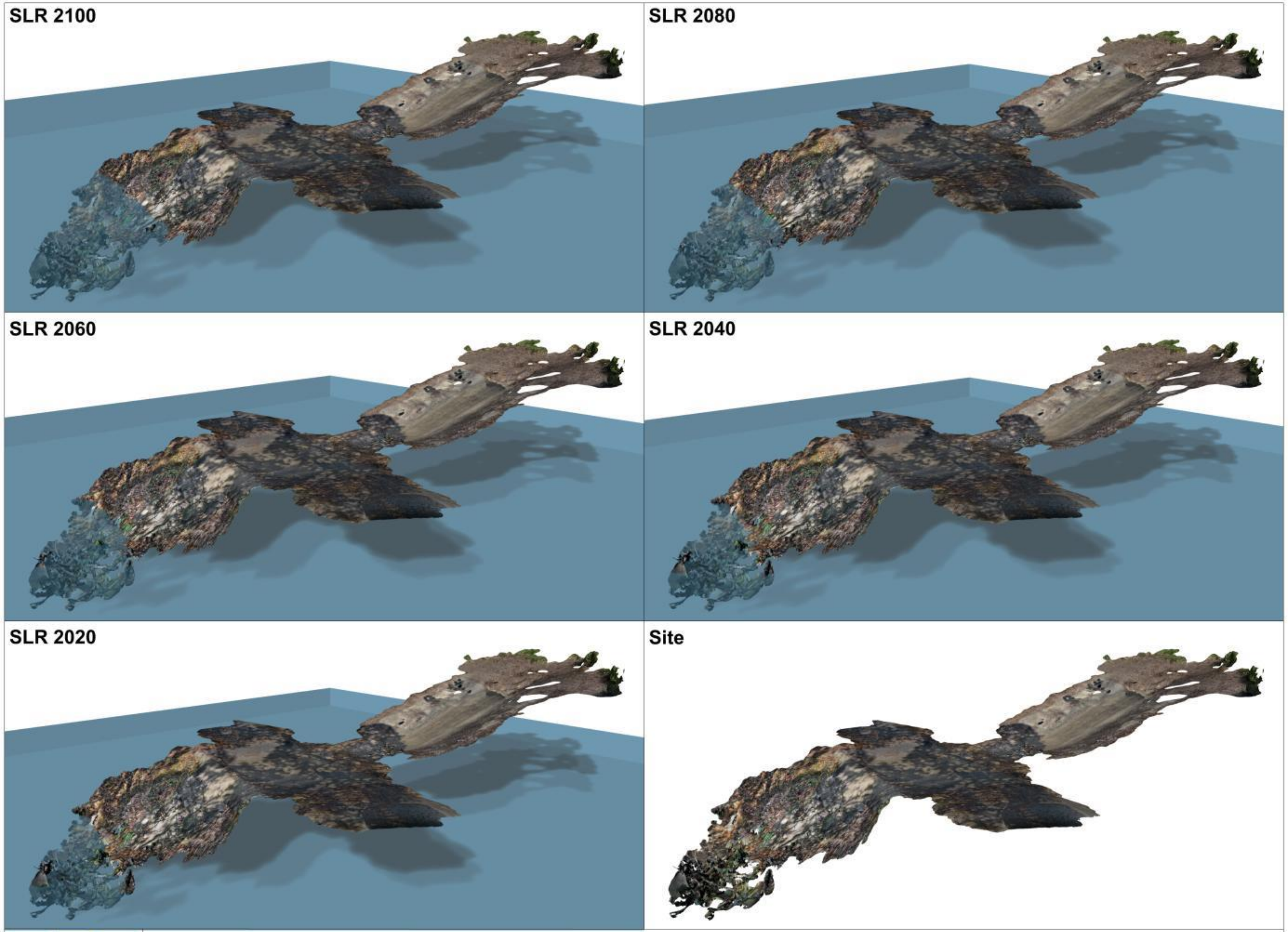

Figure E-8 White Rock Site – Stormwater drain – Coastal Inundation– Asset ID203

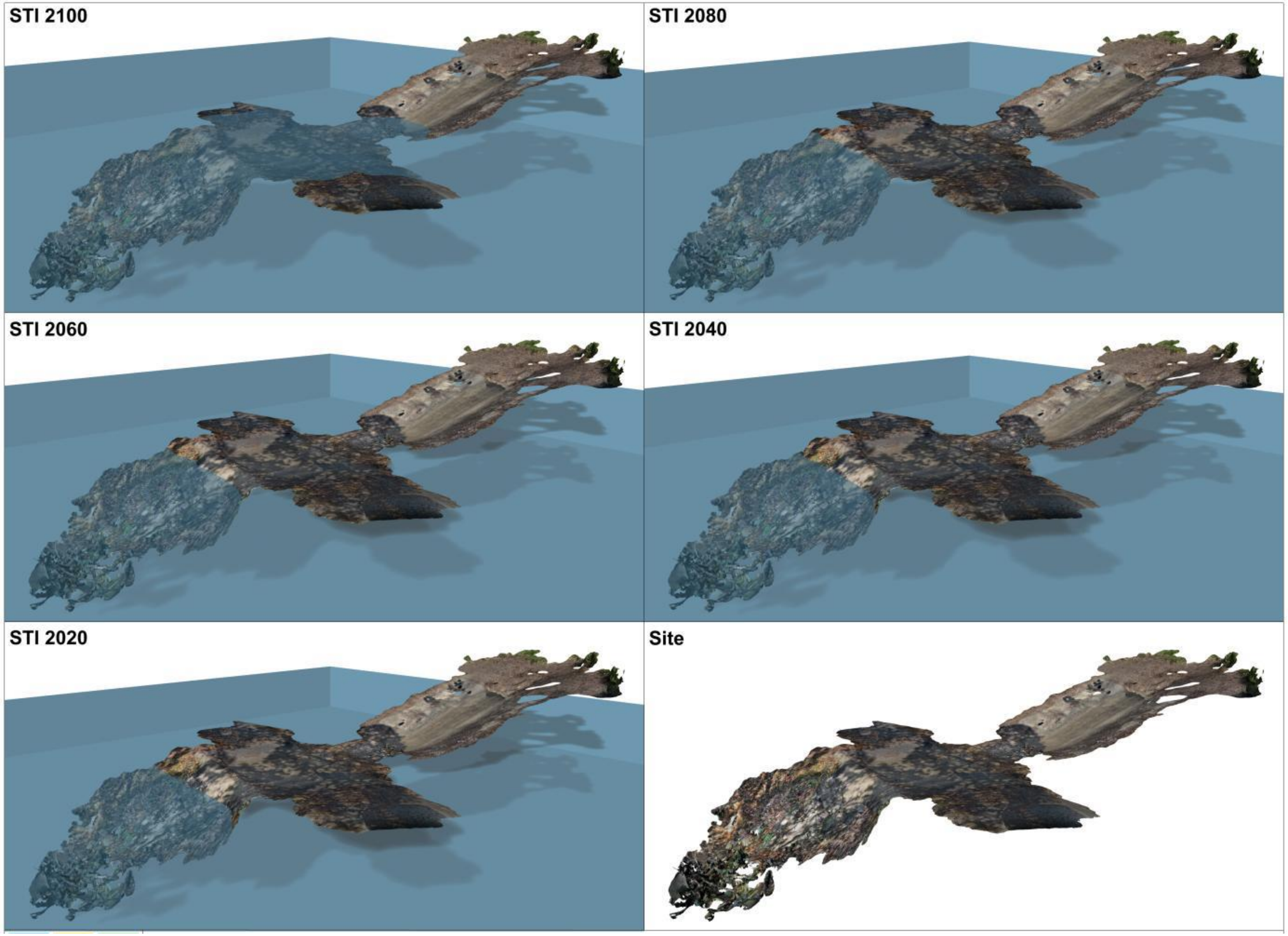

Figure E-9 White Rock Site – Stormwater drain – Coastal Flooding– Asset ID203

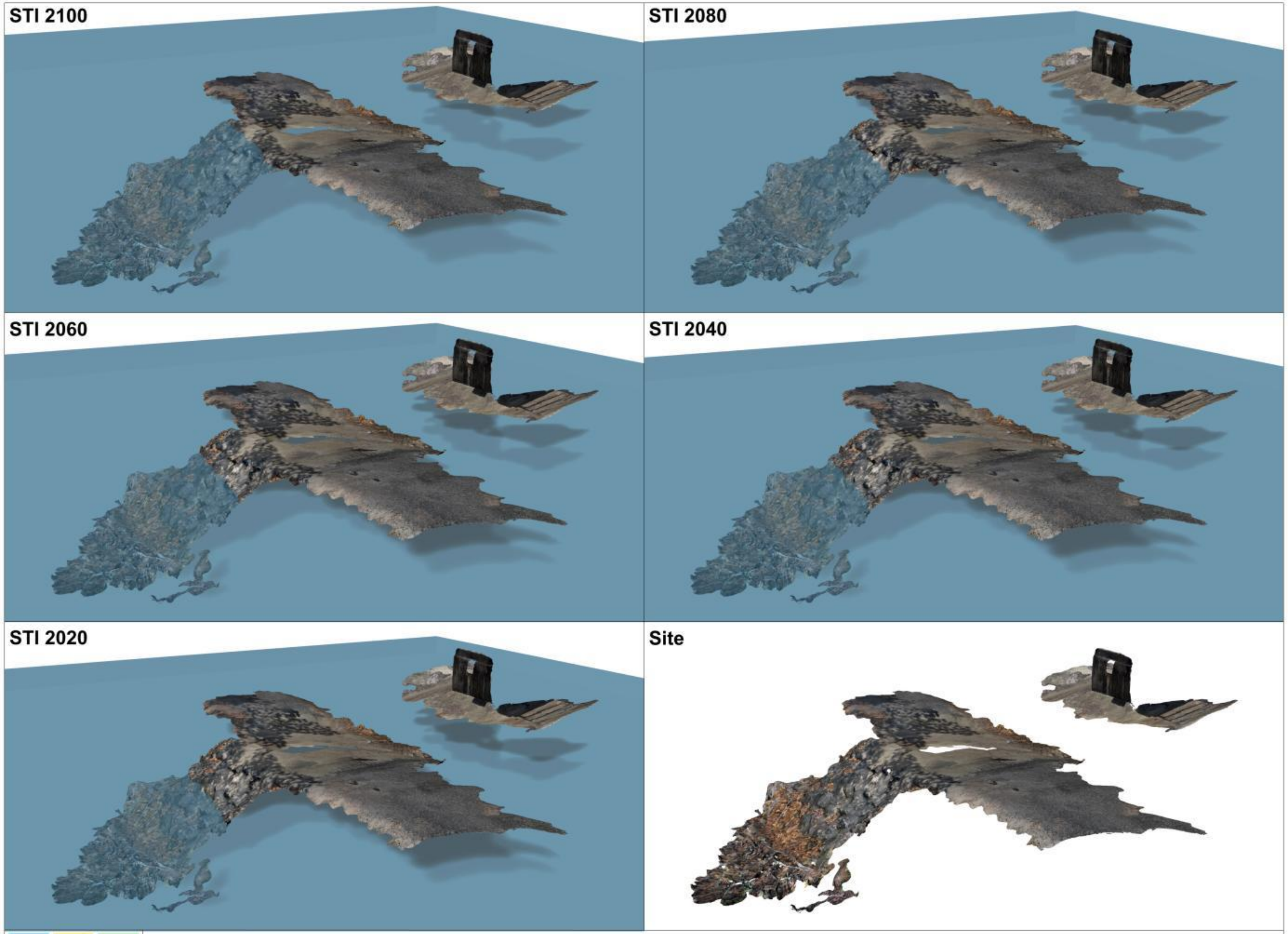

Figure E-10 White Rock Site – Stormwater drain and pump station– Coastal Inundation– Asset ID169,

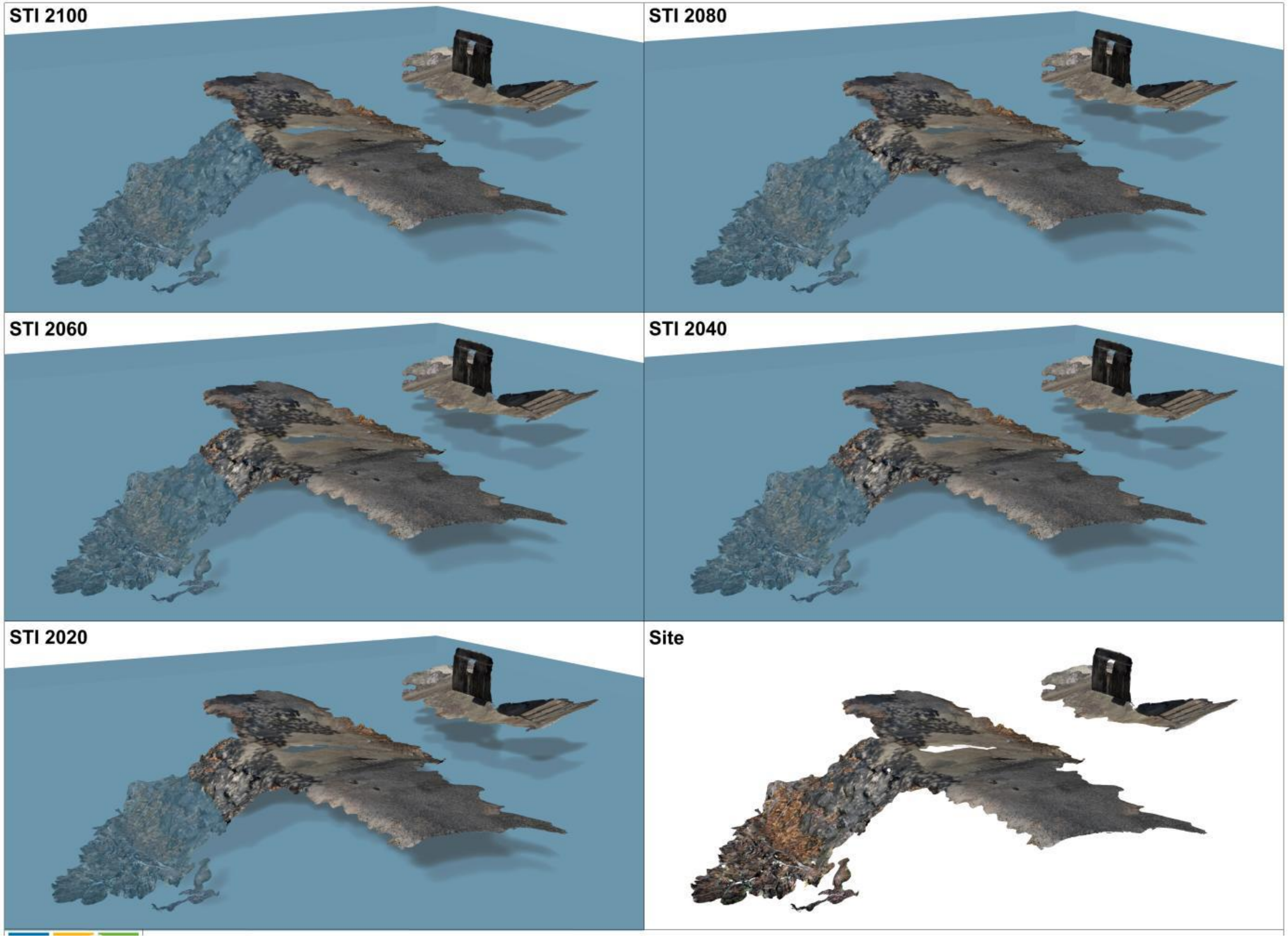

Figure E-11 White Rock Site – Stormwater drain and pump station– Coastal Flooding– Asset ID169, ID177

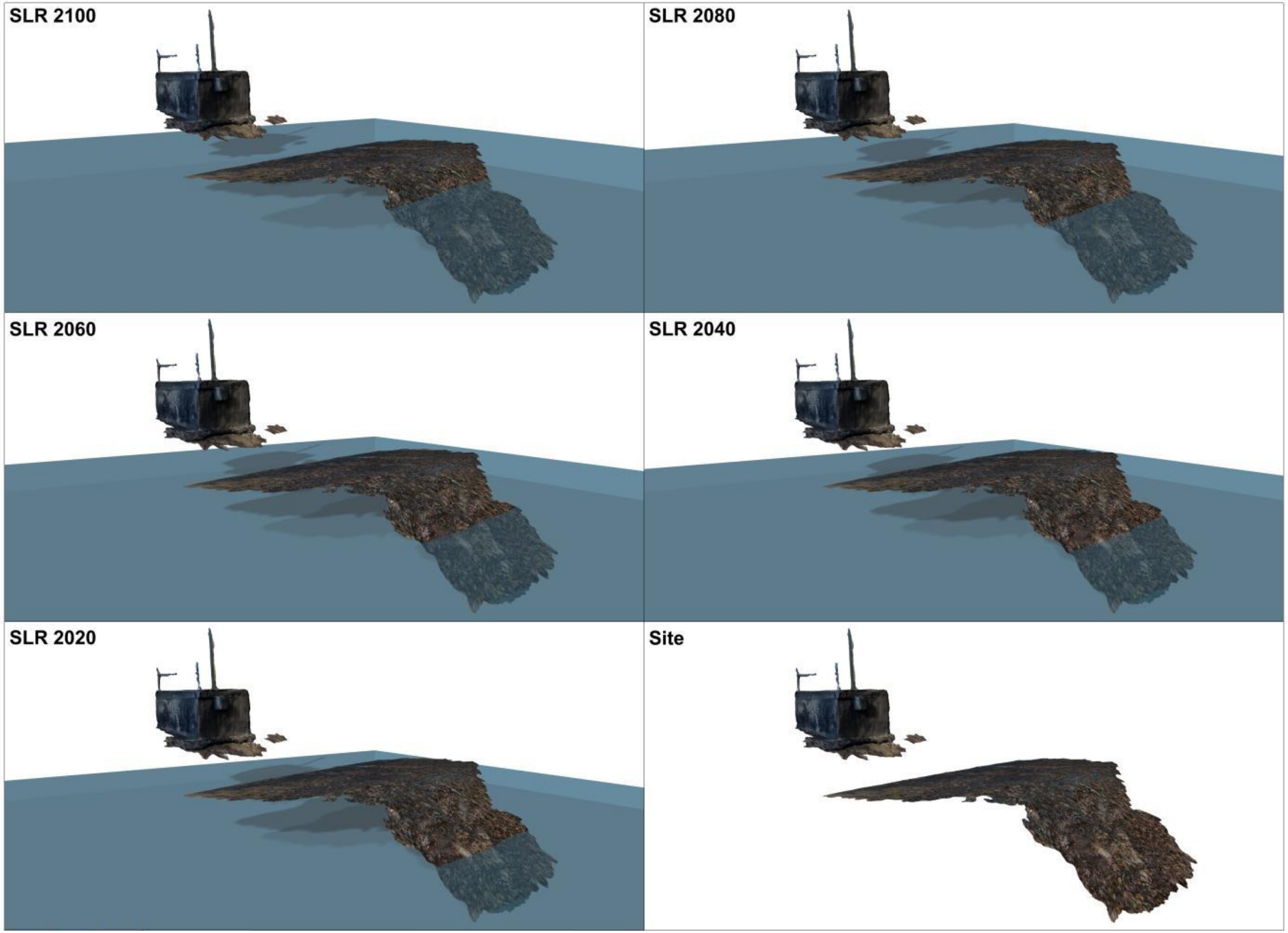

Figure E-12 White Rock – telemetry and pump station– Coastal Inundation

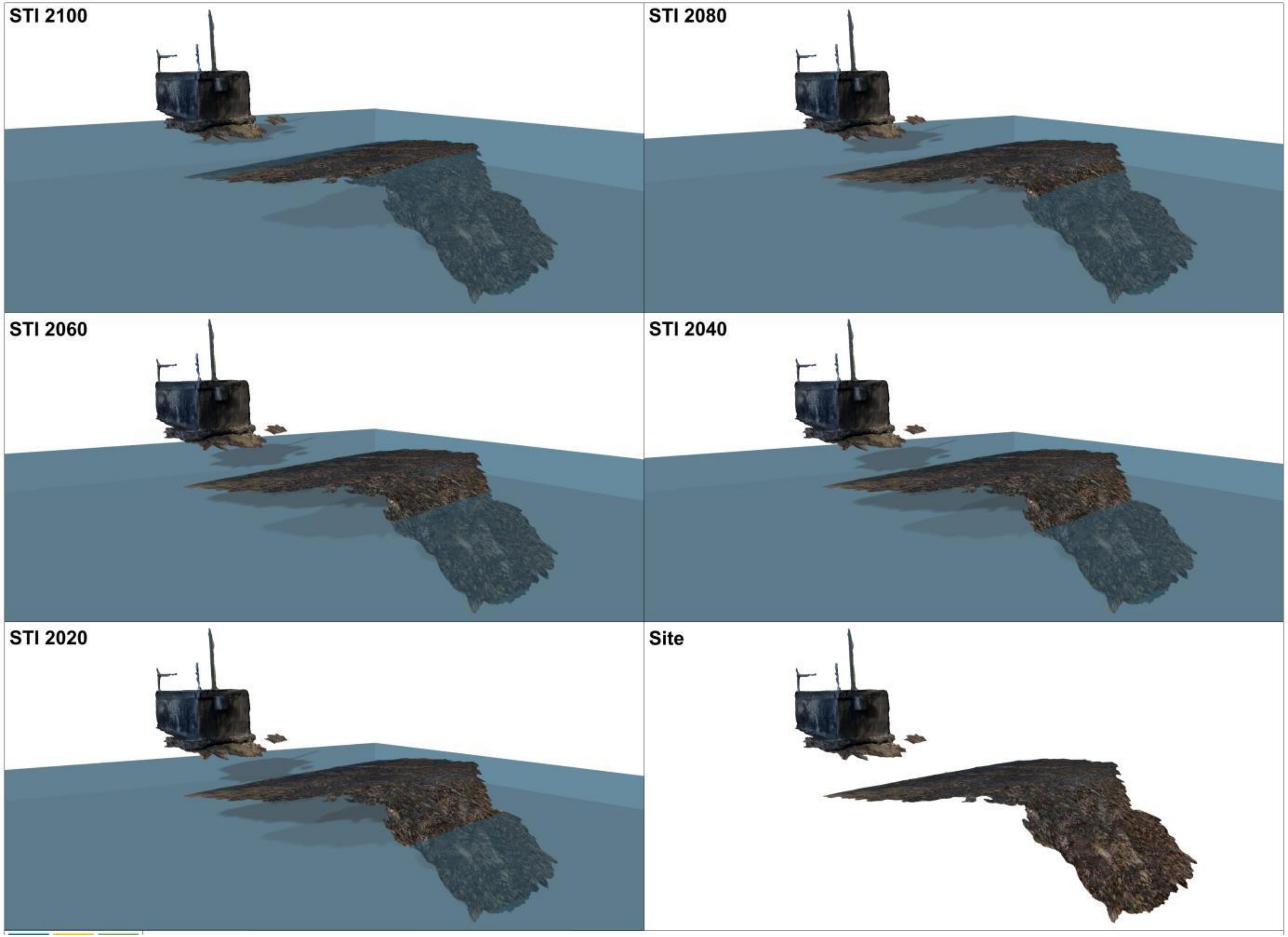

Figure E-13 White Rock - telemetry pump station– Coastal Flooding

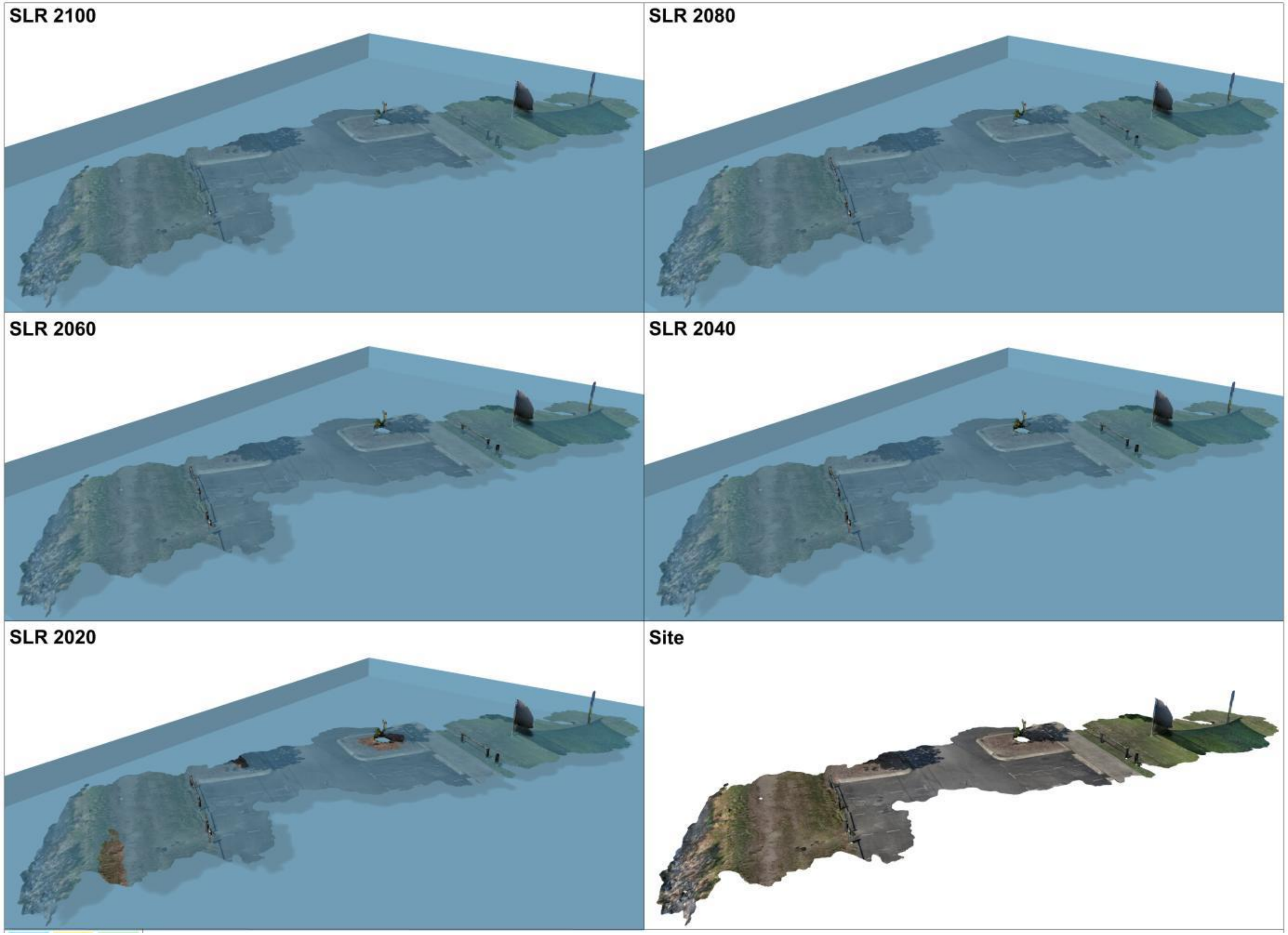

Figure E-14 Endeavour Park – Car Park – Coastal Inundation

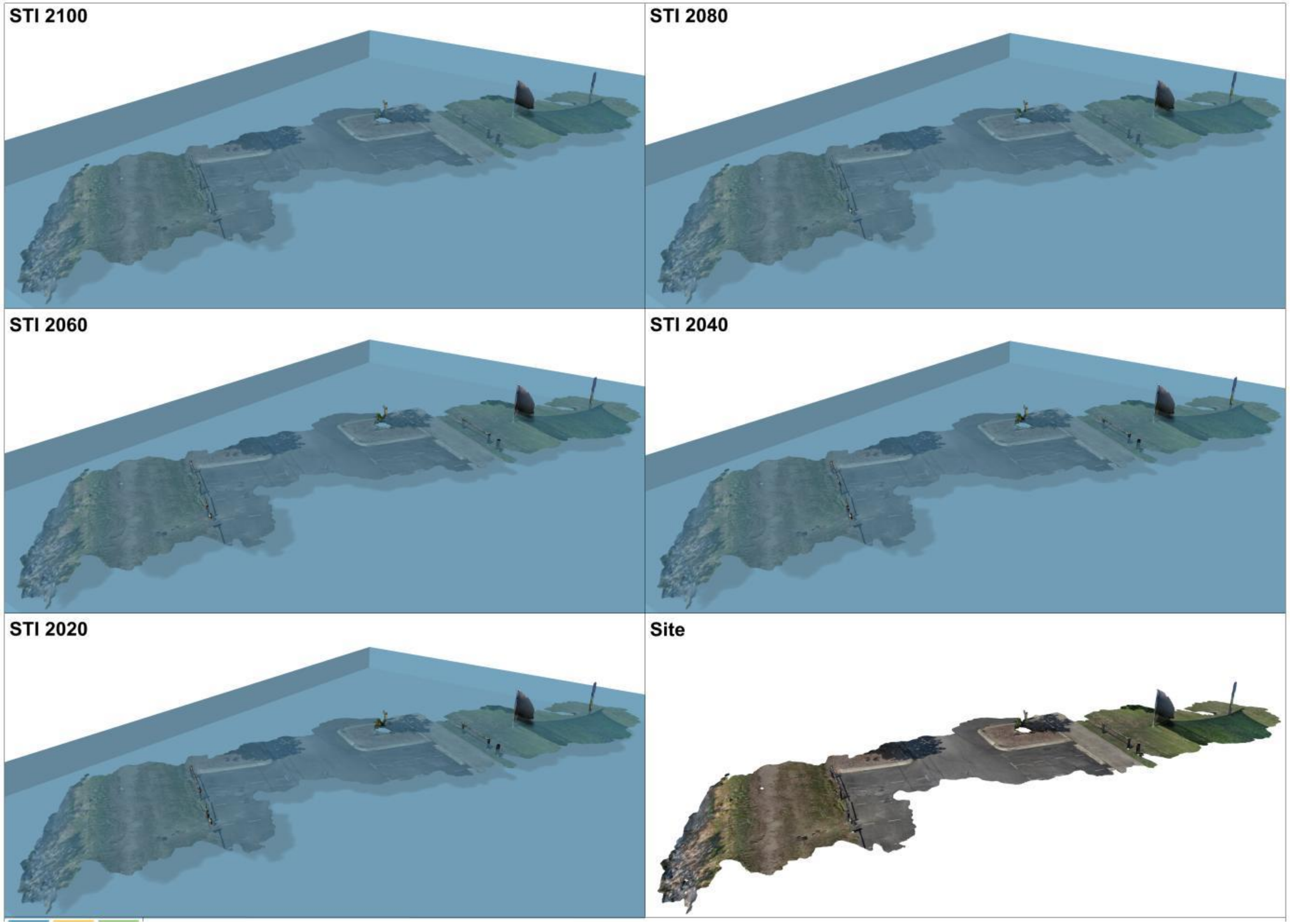

Figure E-15 Endeavour Park – Car Park – Coastal Flooding

APPENDIX E
COST BENEFIT ANALYSIS

Appendix E: Cost-Benefit Analysis

E-1 Economical parameters

Comparative estimates were prepared to determine which management options are likely beneficial from an economic point of view. These estimates are unsuitable for budgeting and do not include indirect costs and contingencies. Comparative unit rates for supplying and installing material and waste per cubic metre are provided below.

- Reclamation fill $80.00 per m^3
- Armour $250.00 per m^3
- Clean-up $500.00 per m^3
- Relocation $100.00 per m^3
- Insured sum:
  - Portsmith Material Recovery Facility $5,000,0000
  - Portsmith Glass Processing Facility $2,500,000
  - Buildings, containers, or material stack $20,000
  - Toilet bloc $10,000
  - All other assets $250

The cost-benefit of each coastal adaptation option is presented in net present value (NPV) terms. NPV is a standard economic analysis to compare options with time-variable costs and benefits. It allows for adjusting all future economic considerations to present-day dollars for a more direct comparison. This relates to the time-value of money, as planned expenses in the future are, in a sense, cheaper than equivalent costs today.

The real discount rate chosen for this project was 4%, with sensitivity analyses at 7% and 2%. This decision was based on similar assessments, the very long timeframe of analysis, and concerns about valuing future spending so low, which is at odds with resilient coastal planning principles. A 7% discount rate is typically compatible with Infrastructure Australia recommendations. This discount rate is high and has been subject to several reviews and updates over the past 5 years because such a high discount rate tends to delay infrastructure decisions, which is risky when environmental and social consequences of not carrying out the project are significant, such as this landfill management study.

The uncertainty around the CBA estimates and assumptions made grows with time. Cost estimates beyond 2040 should be viewed as indicative trends only. Long-term coastal adaptation pathways should be monitored and updated regularly.

The insured sums have been set conservatively, as some of these assets may not be covered or only in an aggregate value, and flooding damage could exceed these insured costs. These costs were considered to capture damage beyond the potential cost of cleaning up and recovering solid waste, capping or armouring material.

Furthermore, sensitivity testing was used to understand the influence of these unit rates on the selection of management options.

E-2 Business as Usual

Clean-up following flooding or inundation underpins the "Business As Usual" management option, which consists of relying on the existing capacity of each site to coastal hazards without further intervention. The cost of clean-up was estimated based on the volume of landfill material eroded for the 100-year ARI storm flood (as per Table 4-8) plus the structure loss estimated from the sample stage damage curve of the Disaster Loss Assessment Guidelines (Australian Disaster Resilience Handbook Manual 27, Figure 1), scaled by the encounter probability of this storm and for each planning horizon considered. The flood hazard accumulates over time as per Table 5-2. The effect of adding the structural loss is significant for the Portsmith site because of the Material Recovery Facility and Glass Processing Facility in the coastal hazard zone.

Table G-1 shows the approximated NPV damage cost of business as usual, including a 4% discount rate for the planning horizon.

Table G-1 NPV cost of "Business as usual" management option

	2020	2040	2060	2080	2100
Portsmith	$13,000	$94,600	$127,000	$247,000	$227,000
Yorkey Knob	$841	$19,900	$52,600	$86,700	$130,000
Machans	$2,530	$29,600	$46,100	$52,400	$55,900
White Rock	$2,100	$22,800	$27,500	$38,500	$44,100
Endeavour	$2,120	$23,700	$34,000	$34,700	$28,300
Aeroglen	$1,270	$2,620	$4,160	$4,990	$8,920
Mann Street	$17,100	$16,500	$18,100	$15,800	$15,000
Barlow Park	$12,500	$15,100	$19,700	$18,900	$16,600
Esplanade	$485,000	$6,040,000	$8,300,000	$8,670,000	$7,250,000
Holloway	$1,230	$16,500	$29,400	$29,900	$26,800

The Business-as-usual cost increases over time as the likelihood of the storm increases and the severity of coastal flooding and inundation increases. The damage potential is most substantial at the Esplanade site, representing over 90% of the clean-up effort, which is a direct consequence of the exposure of the site to coastal erosion.

While these costs appear modest, it is essential to consider that those have been factored by Table 5-2, as such, the damage costs are 100 times higher for planning horizon 2020 than suggested in Table G-1. It is also important to consider that several tropical cyclones will likely occur over time and that this estimate covers only the cost associated with one storm event. Possibly, several extreme storms could occur over the next 80 years.

Table G-2 shows the event-based exposure for the Esplanade and all other coastal landfill sites, highlighting the increased exposure of the Cairns Esplanade.

Table G-2 Event-based exposure

	2020	2040	2060	2080	2100
Esplanade	$48,500,000	$33,600,000	$25,100,000	$19,300,000	$13,200,000
All other sites	$5,270,000	$1,340,000	$1,090,000	$1,180,000	$1,010,000

E-3 Waste Removal

Table G-3 provides the estimated NPV costs for the removal of each landfill site, considering the unit costs and discount rate in Section 6.3.1.

Table G-3 Cost of waste "removal" management option

	2020	2040	2060	2080	2100
Portsmith	$170,000,000	$77,600,000	$35,400,000	$16,200,000	$7,380,000
Yorkey Knob	$16,000,000	$7,300,000	$3,330,000	$1,520,000	$694,000
Machans	$10,000,000	$4,560,000	$2,080,000	$951,000	$434,000
White Rock	$25,000,000	$11,400,000	$5,210,000	$2,380,000	$1,080,000
Endeavour	$22,500,000	$10,300,000	$4,690,000	$2,140,000	$976,000
Aeroglen	$6,200,000	$2,830,000	$1,290,000	$589,000	$269,000
Mann Street	$18,000,000	$8,210,000	$3,750,000	$1,710,000	$781,000
Barlow Park	$1,000,000	$456,000	$208,000	$95,100	$43,400
Esplanade	$1,000,000	$456,000	$208,000	$95,100	$43,400
Holloway	$200,000	$91,300	$41,700	$19,000	$8,680

E-4 Reclamation

Figure G-8 shows a diagram of the Reclamation management option.

The landfill surface is raised above flood level, and coastal protection work is built along each landfill site's submerged perimeter. The reclamation level is raised above wave actions, with only minor overtopping allowed on the reclamation. An additional freeboard of 0.6m was considered for the reclamation fill estimate for each planning horizon. As sea level rise and flooding risk heightened, more fill and armour are required.

The armouring revetment was parametrised based on depth-limited waves at the toe of the levee and the Hudson armourstone stability formula for 1:3 (vertical : horizontal) reclamation slope.

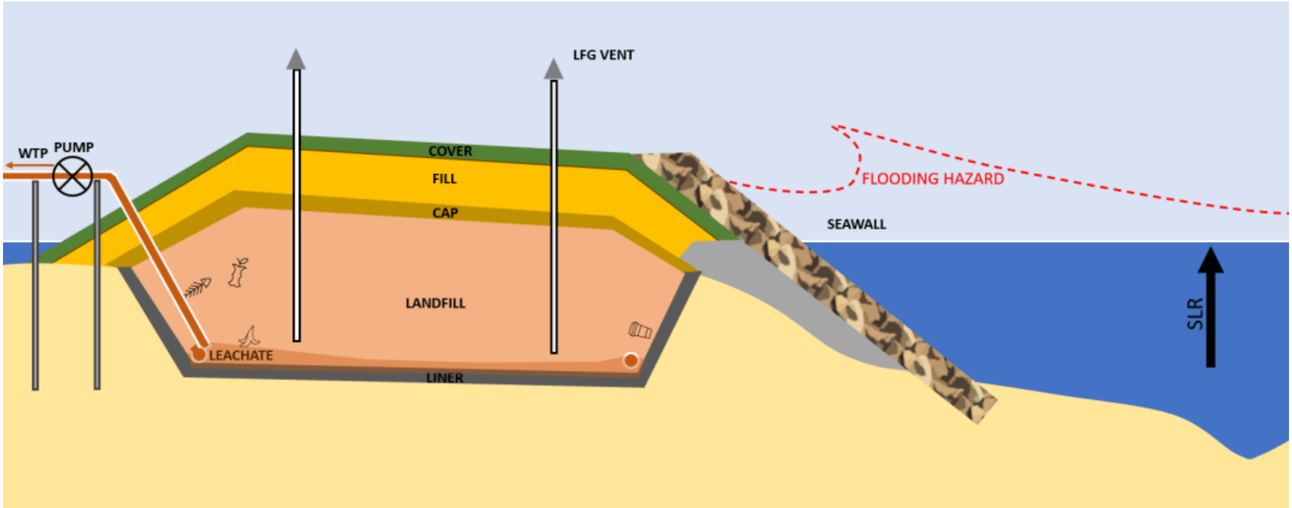

Figure G-8 Reclamation diagram

Table G-4 provides the estimated NPV costs for reclamation of each landfill site, considering the unit costs and discount rate in G-1.

Table G-4 Cost of "Reclamation" management option

	2020	2040	2060	2080	2100
Portsmith	$849,000	$622,000	$442,000	$307,000	$238,000
Yorkey Knob	$13,500	$14,300	$18,300	$20,800	$32,300
Machans	$73,000	$45,000	$36,600	$26,500	$26,300
White Rock	$55,400	$36,000	$25,100	$24,200	$26,400
Endeavour	$397,000	$357,000	$395,000	$452,000	$434,000
Aeroglen	$148,000	$96,300	$72,800	$57,600	$92,400
Mann Street	$4,480,000	$2,390,000	$1,360,000	$776,000	$497,000
Barlow Park	$2,440,000	$1,500,000	$922,000	$584,000	$402,000
Esplanade	$30,500,000	$16,000,000	$8,800,000	$4,780,000	$2,680,000
Holloway	$245,000	$162,000	$110,000	$68,300	$48,000

E-5 Bund

Figure G-2 shows a diagram of the Bund management option. For this option, a coastal levee was parametrised along the submerged perimeter of each landfill site to isolate the site from coastal flooding. The levee was 5m wide at the crest to allow access for maintenance and is set above the level of storm wave actions, with only some minor wave overtopping allowed. In addition, a freeboard of 0.6m was considered for each planning horizon. The levee levels and extents were adjusted along each landfill site as inundation and flooding risk increased. The armouring revetment was estimated based on depth-limited waves at the toe of the levee and the Hudson armourstone stability formula for 1:3 (vertical : horizontal) levee slope.

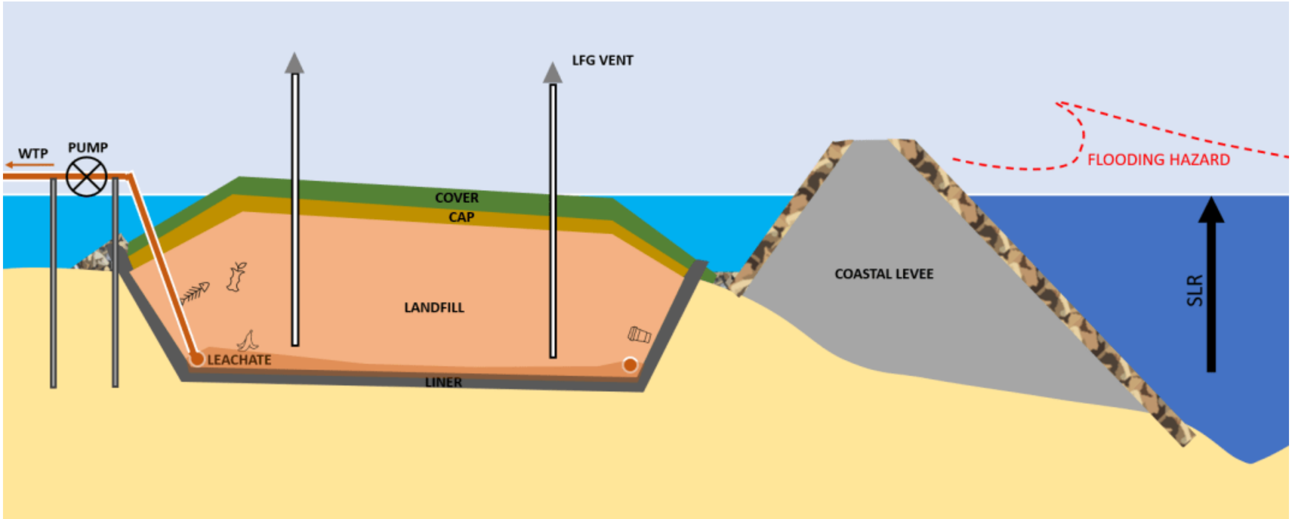

Figure G-9 Coastal levee diagram

Table G-5 provides the estimated NPV costs for bunding each landfill site, considering the unit costs and discount rate in Section 6.3.1.

Table G-5 Cost of "Bund" management option

	2020	2040	2060	2080	2100
Portsmith	$1,390,000	$787,000	$467,000	$285,000	$203,000
Yorkey Knob	$50,000	$49,100	$49,700	$44,400	$51,600
Machans	$165,000	$93,100	$63,400	$39,900	$32,700
White Rock	$143,000	$86,700	$54,600	$47,100	$43,400
Endeavour	$513,000	$302,000	$194,000	$132,000	$91,500
Aeroglen	$138,000	$104,000	$81,600	$69,300	$96,400
Mann Street	$623,000	$356,000	$224,000	$133,000	$88,800
Barlow Park	$788,000	$449,000	$273,000	$161,000	$105,000
Esplanade	$25,200,000	$13,200,000	$7,280,000	$3,930,000	$2,180,000
Holloway	$135,000	$91,400	$73,000	$46,200	$34,000

E-6 Comparison of management option

Table G-6 shows the management option with the highest cost-benefit ratio for each site and each planning horizon.

Table G-6 Lower NPV strategy

	2020	2040	2060	2080	2100
Portsmith	BAU	BAU	BAU	BAU	BUND
Yorkey Knob	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
Machans	BAU	BAU	RECLAIM	RECLAIM	RECLAIM
White Rock	BAU	BAU	RECLAIM	RECLAIM	RECLAIM
Endeavour	BAU	BAU	BAU	BAU	BAU
Aeroglen	BAU	BAU	BAU	BAU	BAU
Mann Street	BAU	BAU	BAU	BAU	BAU
Barlow Park	BAU	BAU	BAU	BAU	BAU
Esplanade	BAU	RELOCATE	RELOCATE	RELOCATE	RELOCATE
Holloway	BAU	BAU	BAU	RELOCATE	RELOCATE

Figure G-3 shows the program in a graphical format, following an annualised estimate over the planning period from 2020 to 2100.

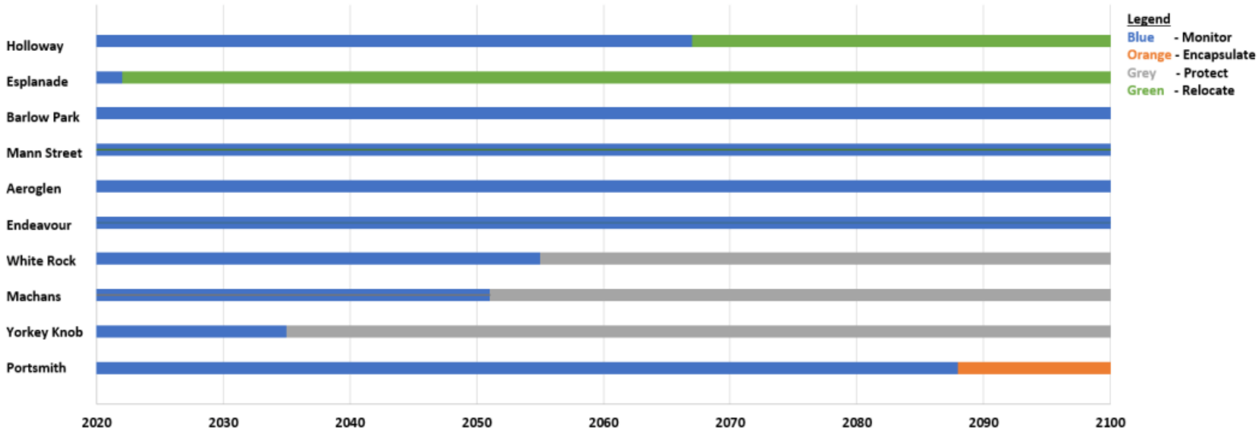

Figure G-3 Lower NPV program

According to this economic model, BAU may be manageable at Portsmith, Endeavour, Aeroglen, Mann Street, and Barlow Park closed landfill sites. However, significant costs will be required for the BAU since remediation following a tropical cyclone is onerous, as discussed in section 6.3.2 and could amount to over 5 million. The detailed annualised estimate shows that relocating landfill waste at the Esplanade will likely be effective after only 2 years of exposure. An ongoing strategy of mapping waste and removing waste is anticipated for this site.

Yorkey Knob would benefit from reclamation works, according to the analysis by 2035. The actual form of the work is more related to revetment works since the volume of reclamation is small compared to the extent of coastal protection works that may be required along Half Moon Creek. A careful monitoring of the site's coastal vegetation and maintenance of this vegetation via suitable Nature Base Solution is likely to be successful in protecting the bund for the foreseeable future. This strategy plays out until 2100.

E-7 Sensitivity analysis

The sensitivity analysis consists of testing three scenarios as follows:

- Scenario 1 - Higher BAU costs to review the sensitivity of the NPV estimate to increased and compounding cost of damage and tropical cyclones. The base case methodology does not consider a wide range of flooding events or the cumulative impact of several flooding events, and this scenario provides an additional level of resilience of the base case.
- Scenario 2 - Lower construction costs to review the sensitivity of the NPV estimate to construction material. Market pressures and scheduling of construction works influence the cost of building works. This scenario also simulated the combined increase of BAU and Relocation costs on the analysis.
- Scenario 3 - Increased discount rate to 7% for infrastructure development and 4% for BAU scenario. These variable discount rates allow intergenerational equity to be explored since the CBA tend to offset the cost of infrastructure development for future generations.
- Scenario 4 – Discount rate reduced to 2%

Table G-7 shows the result of scenario 1, which consists of an increased clean-up cost rate from $500 to $2,000 per cubic metre. The cells highlighted in orange show the difference with the base case presented in section G-6.

Table G-7 Sensitivity analysis – increased damage

	2020	2040	2060	2080	2100
Portsmith	BAU	BAU	RECLAIM	BUND	BUND
Yorkey Knob	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
Machans	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
White Rock	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
Endeavour	BAU	BAU	BAU	BAU	BUND
Aeroglen	BAU	BAU	BAU	BAU	BAU
Mann Street	BAU	BAU	BAU	BAU	BAU
Barlow Park	BAU	BAU	BAU	BAU	BAU
Esplanade	RELOCATE	RELOCATE	RELOCATE	RELOCATE	RELOCATE
Holloway	BAU	BAU	RELOCATE	RELOCATE	RELOCATE

Table G-8 shows the results of Scenario 2, considering the reduced unit cost of fill material from $80 down to $50 per metre cube and of revetment armouring from $250 down to $150 per metre cube. The cells highlighted in orange show the difference with the base case presented in section 6.3.6.

Table G-8 Sensitivity analysis – reduced adaptation costs

	2020	2040	2060	2080	2100
Portsmith	BAU	BAU	BAU	BUND	BUND
Yorkey Knob	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM

	2020	2040	2060	2080	2100
Machans	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
White Rock	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
Endeavour	BAU	BAU	BAU	BAU	BAU
Aeroglen	BAU	BAU	BAU	BAU	BAU
Mann Street	BAU	BAU	BAU	BAU	BAU
Barlow Park	BAU	BAU	BAU	BAU	BAU
Esplanade	BAU	RELOCATE	RELOCATE	RELOCATE	RELOCATE
Holloway	BAU	BAU	BAU	RELOCATE	RELOCATE

Table G-9 shows the results of Scenario 3, with varying discount rates applied. The cells highlighted in orange show the difference with the base case presented in section G.

Table G-9 Sensitivity analysis – discount rate

	2020	2040	2060	2080	2100
Portsmith	BAU	BAU	BAU	BUND	BUND
Yorkey Knob	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
Machans	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
White Rock	BAU	RECLAIM	RECLAIM	RECLAIM	RECLAIM
Endeavour	BAU	BAU	BAU	BUND	BUND
Aeroglen	BAU	BAU	BAU	BAU	BAU
Mann Street	BAU	BAU	BAU	BAU	BUND
Barlow Park	BAU	BAU	BAU	RELOCATE	RELOCATE
Esplanade	BAU	RELOCATE	RELOCATE	RELOCATE	RELOCATE
Holloway	BAU	BAU	RELOCATE	RELOCATE	RELOCATE

Scenarios 2 and 3 typically accelerate the CBR > 1 of interventions by 20 years. However, the type of management option remains unchanged from the base-case CBA. In Scenario 3, Endeavour Park and Mann Street appear to benefit from bunding, while the relocation of waste at Barlow Park is cost-effective beyond 2080. These changes are not significant considering that the CBA is based on high-level comparative PV cost estimates, which are only valid for up to 20 years.

Also, the intergenerational equity perspective is remarkably complex despite the relatively simplistic formulation of scenario 3. The current state of infrastructure and development may not have been possible without waste disposal in the existing closed landfill sites. The evolution of waste valuation technology is such that this solid waste may become a resource for various recycling and power generation schemes.

Scenario 4 provided no specific changes from the base-case results provided in section G-6.

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