University of Southern Queensland

Faculty of Health, Engineering and Sciences

Evaluation of engineering solutions to protect Cairns from coastal inundation due to storm surge and sea level rise

A dissertation submitted by

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Abstract

Cairns is a very low-lying city that faces an uncertain future due to the threat of inundation from cyclonic storm surge and climate change induced sea level rise. The first objective of this study is to identify engineering technologies to protect the city. The second and main objective is to evaluate seawall alternatives and identify the best seawall solution to construct along the Cairns Esplanade. The main objective of this project was achieved by dividing the project into three tasks: (1) detailed review of literature to identify protective seawall technologies around the world; (2) shortlisting of identified technologies based on specific requirements in Cairns; and (3) evaluation through an Analytical Hierarchy Process.

After evaluating various types of seawalls against multiple criteria including aesthetics, water and wave resistance, durability, foot print and sustainability it was determined that a curved, vertical concrete seawall was the best choice for the Cairns Esplanade. This option best fits in with the requirements to protect the city from coastal inundation whilst also maintaining the Esplanade's position as a premium tourist and social destination that is central to Cairn's continuing economic prosperity. It was also determined that construction of the seawall should occur as part of a broader project involving reclaiming and raising land and hardening infrastructure. As the project would need to be completed in stages over an extended period a temporary flood wall solution was also evaluated. The NoFloods barrier tube was identified as a very adaptable temporary solution to fill gaps whilst awaiting completion of the permanent wall. The NoFloods barrier tube is easily stored and can constructed very quickly with little manpower just prior to a cyclone impacting the city.

The city already regularly floods during king tide events and narrowly escaped catastrophe in 2011 when a cyclonic storm surge arrived at low tide. The risk to Cairns is severe and action to implement the recommendations of this report need to be taken immediately.

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Chapter 1: Introduction

Cairns is a vibrant tropical city of 168,449 people (Cairns Regional Council, 2020). It is the regional and economic centre of Far North Queensland, servicing a large geographical area including remote western towns, and up to Cape York and the Torres Strait islands. The regions unique and diverse natural environment including, World Heritage listed ancient rain forests and the world-renowned Great Barrier Reef have made Cairns a premium, internationally recognised, tourist destination. Over five million passengers (prior to Covid-19) pass through Cairns Airport each year (Cairns Airport, 2021).

The city's idyllic weather is ideal for outdoor living and nature-based activities. Its location on a narrow coastal plain between the Coral Sea and a steep 400m high rainforest covered escarpment, and nearby palm fringed beaches allow residents and visitors to enjoy a relaxed tropical lifestyle. The popular tourist strip along the Esplanade (Figures 1.0 to 1.2) is a hive of activity with a multitude of hotels, bars, cafes, restaurants, parklands and the iconic Esplanade swimming lagoon providing the social heart of the city during the day and at night.

Figure 1.0: The Cairns Esplanade and parklands with the CBD, tourist hotels, social facilities and regional hospital (centre of photo) (Cairns Regional Council Master Plan 2018)

Figure 1.1: The iconic swimming lagoon is the center piece of the Cairns foreshore. (Smith 2021)

Figure 1.2: The seaside lagoon is a key social destination and tourist drawcard (Smith 2021)

1.1 The Problem

Cairns is a very low-lying city and faces an uncertain future due to the threat of inundation from the ocean. The city experienced a lucky escape and received a warning of what lies ahead in 2011 when the edge of Tropical Cyclone Yasi skimmed past the city and the accompanying 1 metre storm surge fortunately arrived on an outgoing tide. This warning has largely been ignored.

In October 2020, James Cook University associate professor and geoscientist Jonathan Nott raised the issue again. He stated that Cairns faced a potential catastrophe. A tidal surge associated with a direct hit from a severe tropical cyclone would wipe out the Cairns CBD and low-lying suburbs. Dr Nott said Cairns, "couldn't have been more poorly designed" to sustain a big hit.

"There is nowhere else in this country, or even in the high-income nations of the world, where you have a city that is so prone, so vulnerable to being impacted by a tropical cyclone" (Professor J Nott, reported by Kristy, S ABC News, 2020).

However, tropical cyclones are not the only threat to Cairns. Rapid climate change is predicted to increase sea levels by 0.8m by 2100, as well as increase the frequency of severe category 4-5 cyclones and other severe weather events.

Historically, people around the world adapted to rising sea levels and changing coastlines by moving somewhere else. This time will be different. The world's coastlines are lined with cities, ports and infrastructure - the homes and businesses of billions of people. Land further inland is already taken. This time, it will not be easy to pick up our belongings and move somewhere else. It will cause massive disruption and will have to be met with an equally massive and expensive reconstruction effort (Joshua, K et al. 2018).

The Cairns foreshore, Esplanade tourist precinct, central business district and inner suburbs are barely above the astronomical high tide mark and many streets already flood during the highest king tides. Cairns will be amongst the first major cities in the world to face the challenge that climate change and sea level rise brings.

1.2 Gap in knowledge

The risk of inundation from the ocean is not new and many places around the world have implemented strategies (retreat or defend) and technologies (seawalls, raising land etc.) to minimise the risk. However, each location is unique and what works for one city may not for another. There is no agreeance of the best solution. Therefore, the solutions being implemented around the world vary considerably. The suitability and adapting of these strategies and technologies to the localised conditions of Cairns have not been explored. This report addresses this gap.

1.3 Aims and objectives

The primary objective of this dissertation is to evaluate engineering solutions to protect Cairns from storm surge and sea level rise. This was achieved through two sub objectives:

1. Identify engineering solutions to protect Cairns from coastal inundation.
2. Evaluate and identify the best seawall solution for the Cairns Esplanade through an analytical hierarchical process.

1.4 Project significance

The risk to Cairns is well known. The city already floods during king tide events and came close to being devastated by Cyclone Yasi in 2011. However, recent redevelopments along the southern Esplanade were completed without consideration of cyclonic storm surge and future sea level rise. Action is not being taken to address the problem. This project highlights the risks faced by Cairns and provides solutions on how the problem might be addressed. The project also highlights that any solution will take decades to fully implement and the time for action to commence is now.

1.5 Project feasibility and limitations

A literature search has been completed to identify options so the best solutions for Cairns can be determined. As coastal inundation has always been a problem for many cities located on the ocean's shoreline, there is no shortage of ideas and possible solutions. Therefore, the main issue is when to stop the research phase and move to choosing and adapting identified solutions to the Cairns situation. Setting limitations to the scope of the project and keeping to the project schedule ensures ensure that the projects aim and objectives can be achieved in the available timeframe.

Cairns is a long lineal city spread along 38 kms of a narrow coastal plain that includes several outlying beachside suburbs. The project will be restricted to the central city area only. This area contains the key, high value commercial, industrial, airport, seaport, business and tourist areas as well as higher density inner city residential suburbs. This area is the economic driver and essence of Cairns, without which the city would not be the tropical jewel that it is. With this area, Cairns can continue to thrive. Retreat from the central city area is not a viable option.

Additionally, this project is an initial study that provides an understanding of the problem, the scale of the problem and therefore the need for the recommended engineering solutions. Specific technical aspects and design specifications, timeframes and costs will need to be determined in future studies.

1.6 Outcomes and benefits

This project will extend the current body of knowledge to include practical solutions that can be specifically applied to Cairns and incorporated into town planning now. For instance, when infrastructure reaches the end of its life cycle the replacement may incorporate identified solutions.

The identification of solutions that are both achievable and affordable will install confidence in our town planners and leaders that the threat faced by Cairns can be overcome and will encourage them to start the journey of addressing what will become a defining issue in the decades ahead. This may include purchasing land that needs to be set aside for raising or to become part of a future seawalls or levees. The project highlights areas that require further study and the solutions identified may also be able to be applied to other low-lying centres along the Australian coastline.

Overall, the results of the project show that a gradual, incremental implementation of the identified solutions offers a practical solution to the inundation problem Cairns faces. The literature research also shows that construction of a seawall should not be undertaken in isolation. Rather it should be part of a broader strategy that combined work together to provide the protection that Cairns needs. These broader considerations and project implementation recommendations are discussed in Appendix B. These recommendations minimise disruption to residents and business whilst making adapting affordable by spreading the cost over many decades. However, to ensure the safety of residents is maintained, assets and infrastructure are protected and the city's economic prosperity continues, action needs to commence now.

1.7 Report structure

The research project consists of 7 chapters and Appendix B which offers information on how the project might be implemented:

- Chapter 1 is an introduction to the research project. It provides concise background information on the city of Cairns and how the city is under threat from cyclonic storm surge and sea level rise. It then highlights that there is no simple solution to this problem. However, the report aims to identify strategies from around the world that will then be incorporated to plan of engineering solutions that will protect Cairns out to 2100.
- Chapter 2 contains important information required to understand the scale of the problem. It then identifies what government authorities have done, and intend to do to address the problem. This shows the problem has been clearly identified and acknowledged at the highest levels. Initial planning is underway but no investigation into specific solutions to protect Cairns has occurred. This is the gap in knowledge that this report addresses.
- Chapter 3 contains the research part of the project and identifies technologies and strategies being used around the world to protect coastal cities from inundation.
- Chapter 4 discusses preliminary considerations specific to the Cairns locality before providing an initial analysis and evaluation of possible solutions. Solutions that are clearly unsuitable are excluded from further evaluation.
- Chapter 5 sets out an Analytical Hierarchy Process (AHP) to assess 6 alternative seawall designs and determine the best seawall solution for Cairns.
- Chapter 6 sets out an Analytical Hierarchy Process (AHP) to assess 3 modular flood wall designs that can protect Cairns from inundation on a temporary basis until a permanent solution is fully constructed.

- Chapter 7 is the last chapter of the research project and provides conclusions and recommendations for the seawall design along with discussion on the limitations of the report and recommendations for future research.
- Appendix B provides information on additional considerations that should be incorporated into an overall plan and details how the seawall project might be implemented.

1.8 Summary

This chapter provided the background for the research project. It gave a brief introduction to the low-lying coastal city of Cairns and the inundation threat it faces from cyclonic storm surge and sea level rise. It identified the purpose of the report was to identify technologies and strategies and develop a plan of engineering solutions to protect Cairns. The report structure was then summarised and an outline of each chapter presented.

The following chapter details the nature and scale of the threat and what action is being taken by government to address the problem.

Chapter 2: Understanding the problem

2.1 Introduction

This chapter takes a detailed look at the nature and extent of the inundation threat faced by Cairns. The results of a literature review and investigations by the author are summarised and establish that the threat to Cairns is real and action to address the problem needs to commence immediately. Government authorities have acknowledged the threat and initial planning to address the issue have commenced. However, practical steps to address the problem have yet to occur. This chapter commences with an examination of tides as this is the mechanism that most regularly drives inundation and will continue to do so as the tidal zone continues to encroach on the city.

2.2 Tides

Tides are an effect of gravity and occur principally because of how closely the moon orbits the Earth. As the Earth rotates each day, the moons gravity pulls on different parts of the Earth unevenly and in doing so generates tidal forces. These forces stretch and squash parts of the Earth itself and cause the water in the oceans to bulge out on the sides that are closest and farthest away from the moon (Figure 2.0(a)). As the Earth rotates through each bulge once per day, we have two high tides and two low tides each day (SciJinks 2021).

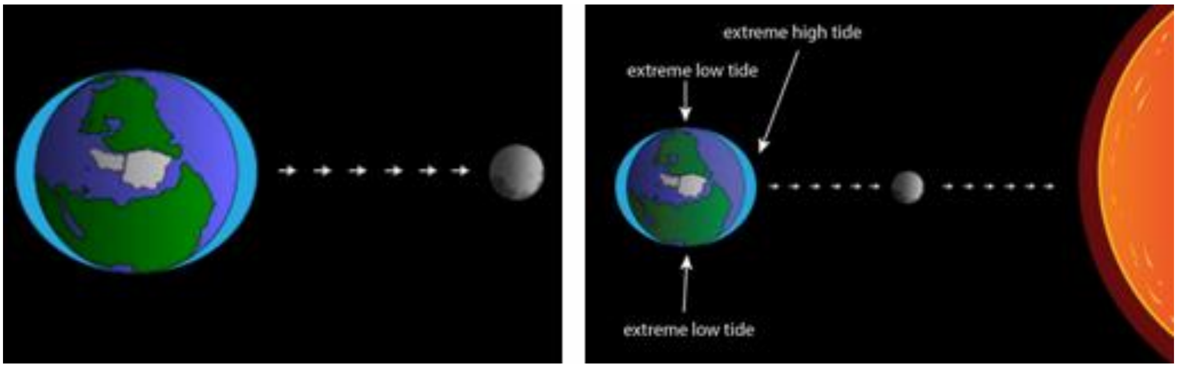


Figure 2.0(a) and 2.0(b): The size of a tides depends on the alignment of the sun and moon (SciJinks 2021)

The Sun's gravity also impacts the Earth's oceans. When the Earth, moon and sun align (Figure 2.0(b)) the combined gravitational pull of the moon and sun on the oceans produces more extreme high tides called spring tides which occur a couple of times a month. The highest of these spring tides are called king tides that generally occur once or twice per year (National Geographic 2021).

Wind and weather patterns also affect tide levels. Water can be moved away from the coast by offshore winds making the tides lower than expected whilst strong onshore winds can push water onto the coast increasing the height of the ocean above what it otherwise would be. High pressure weather systems push down sea levels resulting in lower than estimated tides whilst low pressure systems brought on by strong storms can cause tides to be much higher than predicted (SciJinks 2021). In the case of Cairns, a low-pressure system may develop into a severe tropical cyclone. The combination of low air pressure and strong winds can elevate the ocean level under the centre of the cyclone. This raised dome of water manifests as a storm surge should the cyclone cross the coast. A cyclonic storm surge occurring at high tide or even worse, during a king tide, would result in devastating flooding in Cairns.

2.2.1 King tides

King tides provide a glimpse of the impact that future sea level rise will have on Cairns. As sea levels rise, the normal daily tidal range will increase in height and extend further inland. The inundation that currently only occurs during king tide events will happen on a daily basis during a normal high tide. King tides serve as a warning that climate change is starting to impact our daily lives and can raise community awareness and understanding of how sea level rise will impact Cairns.

King tides can also be useful to identify the lowest lying areas of Cairns that will be the first areas to be impacted by sea level rise. During king tide events the sea level is so high that it comes close to overflowing over the wall that protects the Cairns Esplanade parklands (Figure 2.1).

Figure 2.1: King tide along the Cairns Esplanade on 2 January 2022 (Grant O'Donoghue 2022)

Behind the parklands sea water rises up through the street drainage systems and starts flooding the Cairns Esplanade (Figure 2.2(a)). The greater city area is so low that tidal waters also flow up the creeks (Figure 2.2(b)) that normally drain the city's inner suburbs and industrial areas until they also become inundated with tidal waters.

Figure 2.2(a) and 2.2(b): King tide tidal flows backing up through drainage systems, Cairns 2 January 2022 (Grant O'Donoghue 2022)

The extent and severity of king tide flooding that already occurs along the Cairn's Esplanade tourist strip and CBD is shown in figures x to x. However, king tide flooding is also widespread in many other areas of central Cairns, especially in the key industrial areas shown in figures 2.3(a) to 2.3(h). The photos emphasis how vulnerable Cairn's economic security is with many businesses and much of Cairn's employment and economic activity occurring along the Esplanade tourist strip and industrial areas that are already significantly impacted by regular inundation.

Figure 2.3(a): Water bubbling up through roadside drains during Cairns Esplanade king tide 2014

Figure 2.3(b): Inundation in front of the Cairns RSL, Cairns Esplanade king tide 2014

Figure 2.3(c): Inundation in front of Double Tree Hilton Hotel, Cairns Esplanade king tide 2014
Source: Figures 2.3(a) to 2.3(c) Cairns Post 2014

Figure 2.3(d): Access to fishing fleet, lower Fearnley St. Cairns, king tide 2 January 2022

Figure 2.3(e): Industrial area, Upper Fearnley St. Cairns, king tide 2 January 2022

Figure 2.3(f): Centrelink office and bus stop, Draper St. Cairns, king tide 2 January 2022

Figure 2.3(g): Industrial area, Redden St. Cairns, king tide 2 January 2022

Figure 2.3(h): Industrial area, Tingira St. Cairns, king tide 2 January 2022
Source: Figures 2.3(d) to (h) Grant O'Donoghue 2022

Although localised inundation during king tide events already regularly impacts access to some of Cairns primary business areas several times each year, a much more serious threat comes from tropical cyclones and storm surge events.

2.3 Tropical cyclones and storm surges

A tropical cyclone is a violent rotating storm that forms over warm tropical waters during November to April. They are an annual occurrence in Far North Queensland and often threaten Cairns.

A storm surge is a local rise in seal level, over and above the expected tide level. It is caused by the combined action of severe winds and the low atmospheric pressure that occurs in the centre of severe tropical cyclones. In addition, the sea level closest to the shore will be elevated even further by wave setup. This is the waters shoreward momentum caused by waves and currents. These three factors combine to create the overall water level known as a storm tide (Harper 2001) (Figure 2.4).

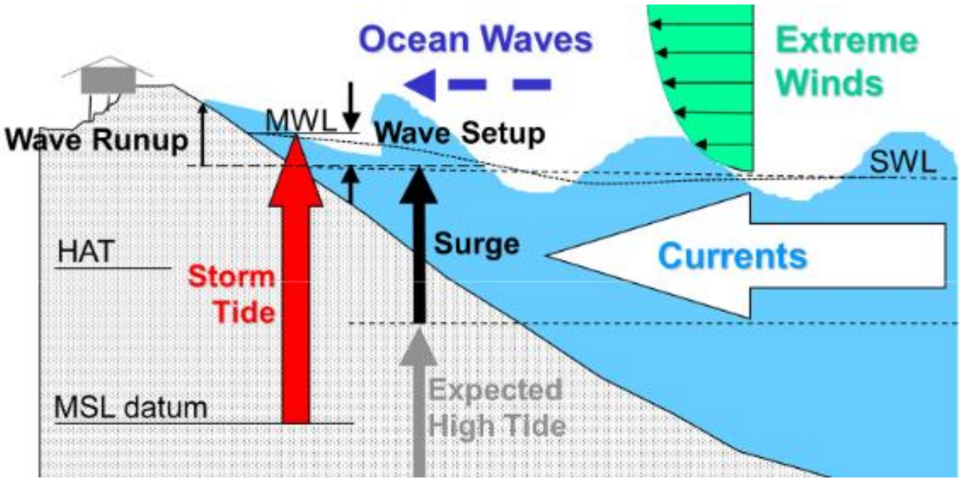


Figure 2.4: Water level components of a storm tide.
MSL = mean sea level, HAT = highest astronomical tide,
MWL = mean wave level, SWL = still water level. Source: Harper 2001

However, the severest damage from a storm tide comes from a fourth factor. Wave run up is the action of waves, whipped up by cyclonic winds, rushing up sloping beaches with enough height and energy to increase water levels over and above the storm tide water level. These high-energy waves crash against shorelines causing considerable erosion and extensive damage to unprotected buildings and roads (DES-Qld Govt, 2018).

Storm tide Inundation impact = astronomical tide + storm surge + wave set up + wave runup

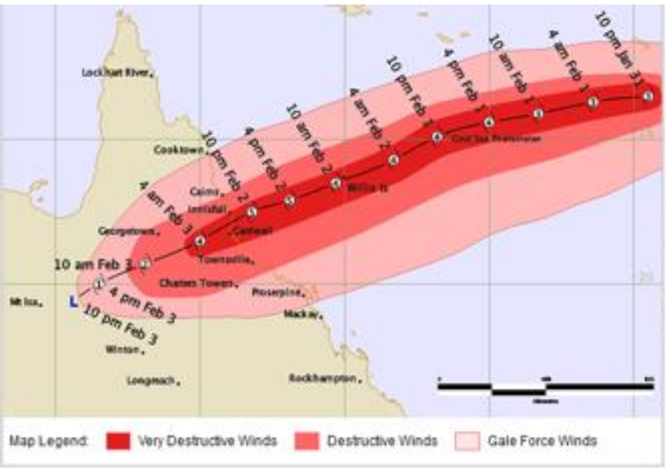
Total impact = storm tide inundation impact + effect of cyclonic winds + torrential rain + flooding

The destructive capacity of a storm tide is therefore dependant on the height of the tide as the cyclone crosses the coast. This will then be exacerbated by wave run up (Qld Govt. 2012).

2.3.1 Tropical Cyclone (TC) Yasi

In 2011, one of the most powerful cyclones to affect Queensland since records commenced made land fall near the small settlements of Mission Beach and Cardwell (Figures 2.5(a-b)). The severe Category

5 system was unusually large at 500 km wide and sustained wind speeds of 205 km/hr with gusts of up to 285 km/hr (BOM, 2021). Despite making landfall in a sparsely populated area, the damage to property and infrastructure was estimated at $800 million (Qld Govt. 2012).



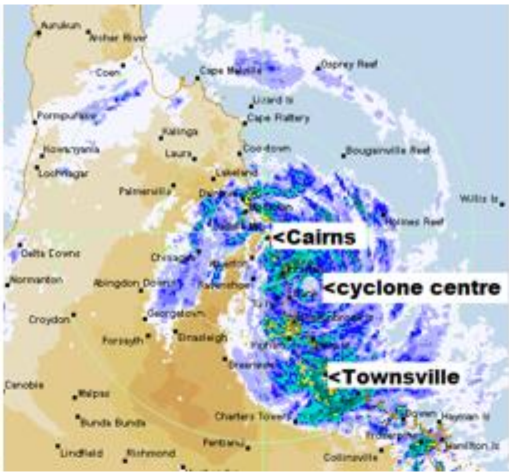


Figure 2.5(a): Cyclone Yasi tracking map showing land fall below Cairns (BOM, cyclone history/Yasi)
Figure 2.5(b): Radar image of Cyclone Yasi crossing the coast (BOM, cyclone history/Yasi)

The power of the storm tide is clearly shown in Figure 2.6. The peak surge occurred around 1.20 am and Cardwell's residents woke to find their foreshore eroded away and parts of the Bruce Highway starting to disappear. Cardwell's storm tide gauges recorded a peak storm surge of 5.33 metres in excess of the expected tide level. However, this was on a receding tide. Had the cyclone crossed the coast at full tide, just 4 hours earlier, the water level would have been almost 3 metres higher (Qld Govt Cyclone Yasi Report, 2012). Had this occurred, the storm tide would have reached much further inland, and much of Cardwell township would have been destroyed by the crashing waves.


Figure 2.6: Damage to Cardwell foreshore with part of the Bruce Highway washed into the ocean by the storm surge that accompanied Cyclone Yasi in 2011 (Dept. Science. Qld Govt Cyclone Yasi Report, 2012)

Figures 2.7(a-b)) show the destruction to marina facilities at Port Hinchinbrook, on Cardwell's outskirts. The sheltered, inland harbour offered little protection as it was overwhelmed by the storm tide. Finally, Figures 2.8(a-d)) show the power of the surging waves at Tully Heads. Sea water, to a depth of just over one metre, surged through the beach side homes and systematically dismantled the seawall, tossing the rock armour onto the lawn. A report by James Cook University's School of Engineering found the buildings started to suffer structural damage when the height of the storm surge was only 200mm above floor level (JCU, 2011).

Figure 2.7(a): Port Hinchinbrook on the outskirts of Cardwell (Local Guides 2021)

Figure 2.7(b): Port Hinchinbrook after Cyclone Yasi 2011
(Dept. Science. Qld Govt Cyclone Yasi Report 2012)

Figures 2.8(a) and 2.8(b): Damage to the bottom level of a house at Tully Heads where armour rocks from the seawall have been washed onto the lawn by the wave energy of Tropical Cyclone Yasi's 5.33 metre storm surge.

Figure 2.8(c): Damage to external walls on seaward side of house

Figure 2.8(d): Damage to single story houses – house on the right has been completely washed away.
Source (4 images): JCU School of Engineering, 2011

Although unfortunate for the small towns devastated by the cyclone, the impact could have easily have been much worse. North Queensland's two major regional centres of Cairns and Townsville are located just north and south of the most impacted areas around Cardwell and Mission Beach (Figure 2.5(b)). Either city, but especially Cairns, would have been devastated by a direct hit at high tide. The minimal damage suffered by both cities is only due to the fortunate path the cyclone followed.

2.3.2 Tropical Cyclone (TC) Yasi and Cairns

Cairns is situated 138km north of where Cyclone Yasi made landfall and missed out on the severest impacts of the storm. However, the city still experienced strong winds and a storm surge of 1.09m battered the Cairns shoreline at about 1.20am (Qld Govt Cyclone Yasi Report, 2012). The receding tide prevented the storm tide surging into the city and saved Cairns from extensive damage. Figures 2.9(a-b)) show waters remained dangerously high in Cairns the following morning when the next high tide occurred. Even though the cyclone crossed the coast over night and was starting to weaken, the tranquil waters of Trinity Inlet were still being whipped up by strong winds. The images give some insight into how close Cairns came to catastrophe. Had the storm surge occurred at high tide, Cairns city would have been inundated and these waves would have been crashing through the buildings along the Esplanade. It is thought provoking to consider that these images come from the dying stages of a cyclone that passed over night, 6-9 hours earlier, and which largely missed Cairns.

Figure 2.9(a): 2011 Cyclone Yasi, Cairns high tide, 6-9 hours after peak storm surge (Our Cairns Coast - Adapting for the Future)

Figure 2.9(b): Waves generated from TC Yasi crash over Cairns Esplanade lagoon pool (Sexton-McGrath, ABC News Report, 2020)

2.3.3 Risk of reoccurrence

In 2013, James Cook University associate professor and geoscientist Jonathan Nott and his colleague Thomas Jagger released a study of the of the beach ridges at Rockingham Bay (Figure 2.10). This is the location where the southern edge of the eye of Cyclone Yasi crossed the coast.

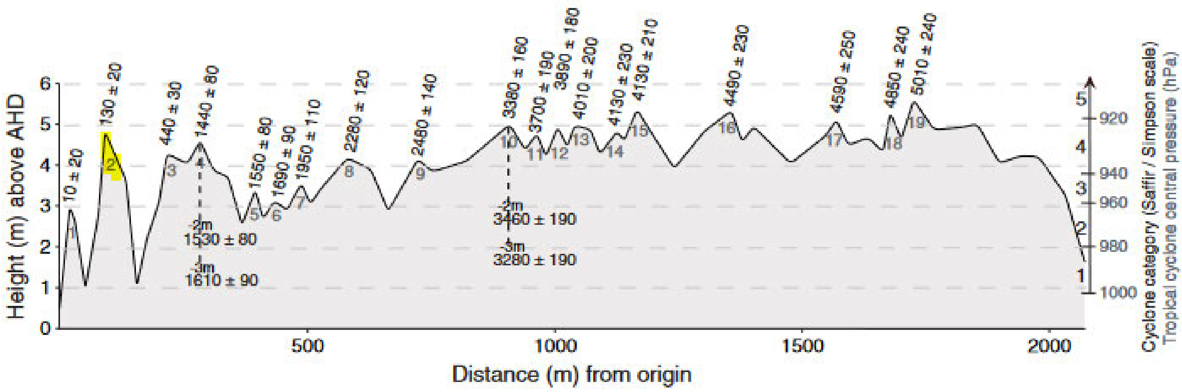


Figure 2.10: Topographic cross-section through beach ridge plain at Rockingham Bay showing elevation and dating of ridges numbered from 1 to 19 going back 5000 years with ridge 1 being the most seaward and sand deposits from Cyclone Yasi on ridge 2. Source: Nott J and Jagger H, 2013

The report found a 30-40 cm layer of sand was deposited on to the highest seaward ridge (ridge 2 in Figure 10) at an elevation of 5.2 m above the astronomical high tide level. They determined that this corresponds to a one in 1000-year event at this location (Nott J and Jagger H, 2013).

Whilst a 5 m storm surge event is extremely rare and the risk of this occurring at any particular location extremely low, this is of little consolation for Cairns which would be seriously threatened by a 1 m storm surge occurring at high tide. Tropical cyclones threaten the North Queensland coast every year. Even severe category 5 cyclone systems are not that rare with three crossing the North Queensland coast in the last 20 years (Cyclone Larry 2006, Cyclone Yasi 2011 and Cyclone Marcia 2015).

The potential risk for Cairns if hit directly by a severe cyclone at high tide is clear. However, Cairns has been lucky, and the city has not had to face these catastrophic consequences. This luck is unlikely to continue into the future as climate change and sea level rise change the risk profile for all coastal communities, but particularly Cairns.

2.4 Climate change and sea level rise

It is usual for climate to change over geological time frames. However, climate research has shown that climate change is not always gradual. Sometimes our climate can change abruptly, due to so-called “tipping points,” causing the Earth’s climatic system to move to a new state of equilibrium over a relatively short time period (Lenton et el, 2019). A mere 6000 years ago the Sahara Desert did not exist. Instead, there were vast grasslands that received plenty of rainfall until shifts in weather patterns transformed the land into some of the driest on Earth (Boos, W. & Korty, R., 2016).

Likewise, sea levels change, and coastlines shift over time. Between 116,000 and 129,000 years ago, global temperatures were around 2°C higher than today and the sea level was between 5 and 10 meters above current levels (Australian Academy of Science, 2021).

Around 21,500 years ago the world was a very different place than today. It was the height of the Ice Age - the last “Glacial Maximum”. Vast ice sheets covered much of Asia, Europe and North America. So much water was transferred from the oceans to the ice sheets that climatic conditions were much dryer, cooler and sea levels were an astounding 120 metres below modern levels (Joshua, K et al, 2018). Since this time, although temperatures have fluctuated, the Earth has seen a clear warming trend, and the melting of the ice sheets continues to this day.

Over the last several thousand years, global mean sea levels have been fairly stable and in the last two thousand years, sea levels have only increased by a few centimetres per century (Australian Academy of Science, 2021). However, Figure 2.11 shows this started to change from around the mid-1880’s. Since that time global sea levels have risen by around 21-24 centimetres (NOAA, 2021). This is an average of around 1.6 centimetres each decade over the last 140 years.

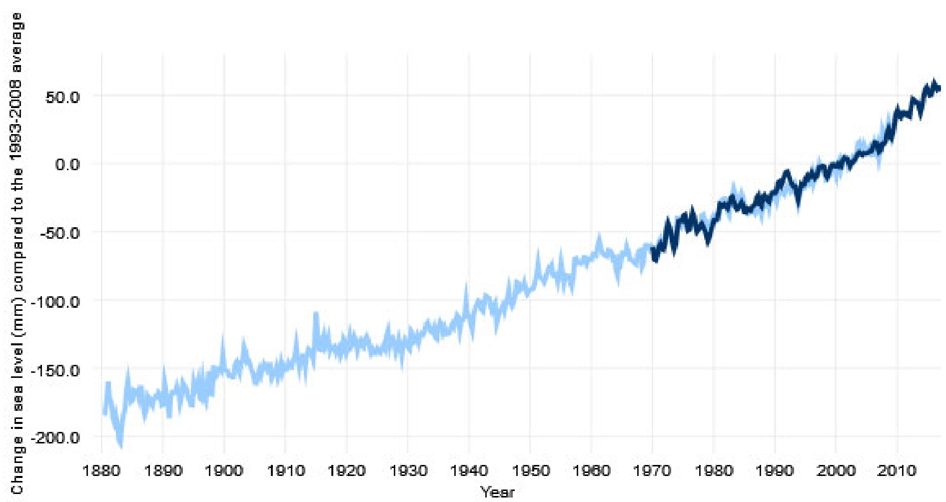


Figure 2.11: Sea level rise since 1880 (Lindsey, NOAA, 2021)

In the last 20 years, both coastal sea-level gauges and satellite measurements indicate that sea level rise has accelerated to around 3 centimetres per decade. According to the Australian Academy of Science, this rise in sea level has primarily been from the thermal expansion of ocean water as our oceans become warmer and the addition of water to the oceans from retreating (melting) glaciers (Figure 2.12).

Additionally, since around 1990, melting of the Greenland ice sheet and more recently the Antarctic ice sheet have further contributed to the accelerating sea level rise (Australian Academy of Science, 2021).

Figure 2.12: Alaska's Pedersen Glacier in 1917 (left) and 2005 (right). By 2005 the glacial lake that existed in 1917 had become grassland and the glacier had retreated to the background. (Lindsey, NOAA, 2021)

Of greatest concern is the rapid acceleration in ice loss from the Greenland ice sheet. During the 10 years from 1992 to 2001, 34 billion tons were lost each year, whilst in the 5 years from 2012 to 2016, this had increased to 247 billion tons per year (NOAA, 2021).

The reason for this increase is global warming. The Australia Government Bureau of Meteorology (BOM) "State of the Climate 2020" report states that Australia's climate has warmed by around 1.44^{o}C since 1910 with 1^{o}C of this increase occurring since 1960 (Figure 2.13). Oceans around the world have warmed by around 1^{o}C (BOM, 2020). The report goes on to say that the recent warming can only be explained by human caused emissions. In particular CO_2 concentrations in the atmosphere have increased from around 280 ppm for most of the last 2000 years to about 410 ppm today (Figure 2.14). They continue to increase by around 2-3 ppm each year.

As a result of the continued warming and melting of the Greenland and Antarctic ice sheets, sea levels are projected to rise at a much faster rate over the next century. If the world is successful in lowering greenhouse gas emissions the sea level rise by 2100 might be restricted to around 30 cm. However, there is little sign of emissions reducing so sea level rise is more likely to be closer to 1.0 m (Figure 2.15).

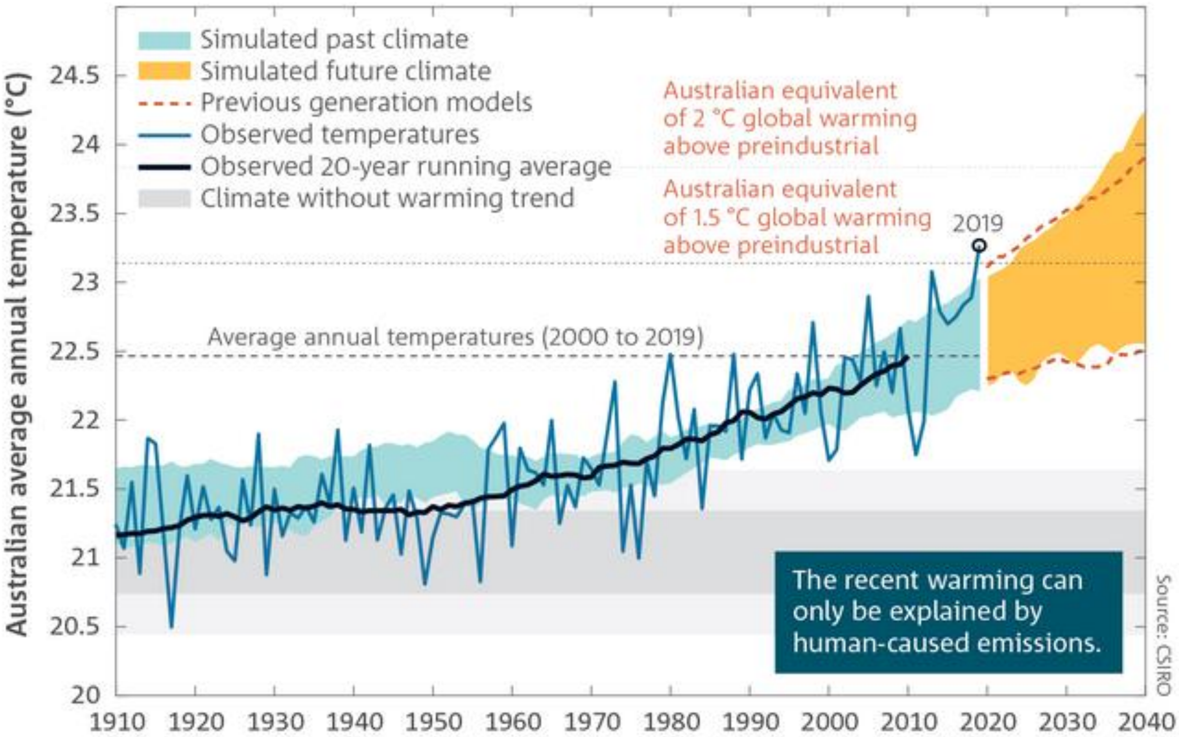


Figure 2.13: Increase in Australian average temperatures since 1910 (BOM 2020)

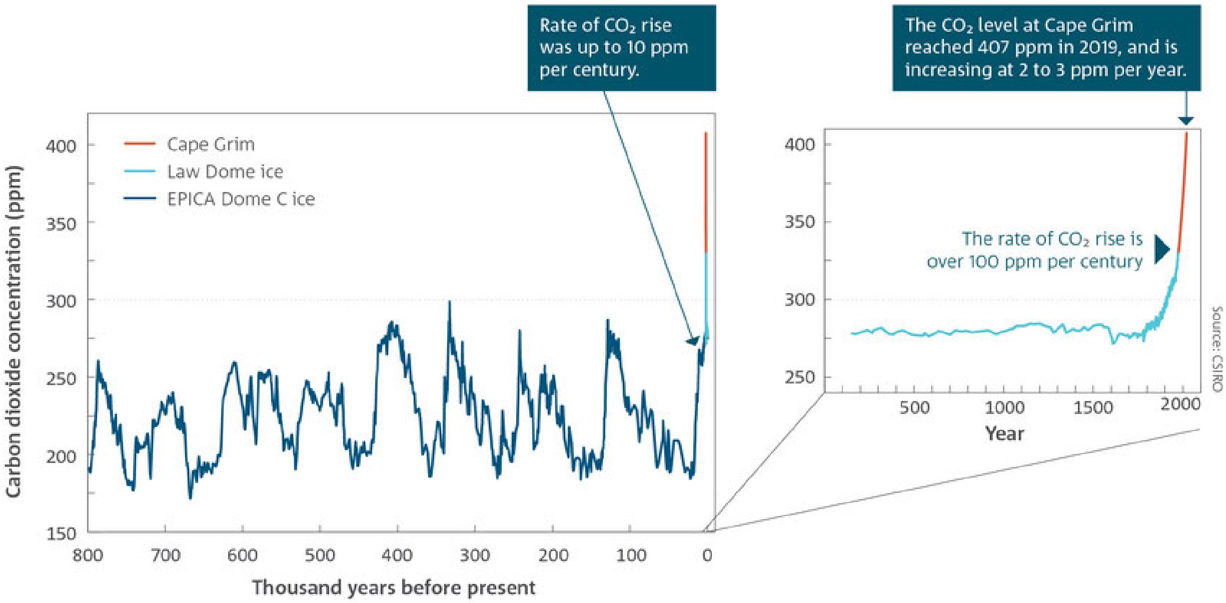


Figure 2.14: Atmospheric CO_2 concentrations, past 800,000 years (left), and 2000 years (right) (BOM, 2020)

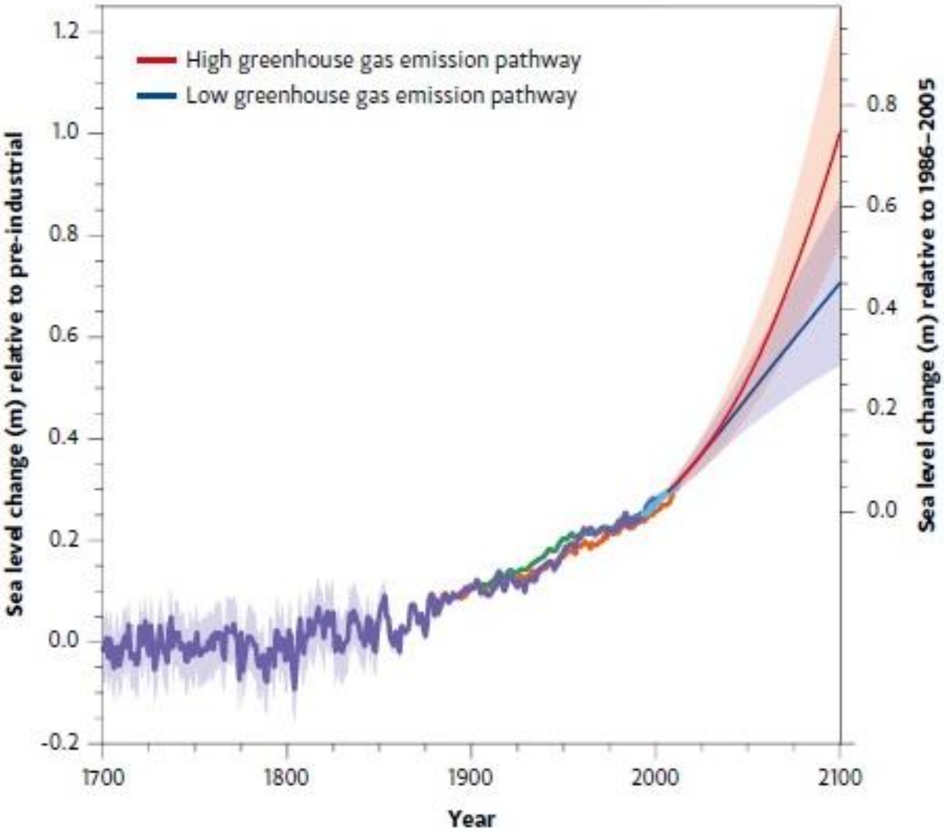


Figure 2.15: Sea level rise projections to 2100 are likely to be in the higher 0.8m range (Australian Academy of Science 2021)

2.5 Queensland Government response

In 2016, in response to the threat from our changing climate and rising sea levels, the Queensland Government launched the QCoast 2100 Program. The purpose of the program is to provide technical support and $13.234 million in funding to encourage and assist 41 coastal councils develop medium to long term strategy and adaption plans to cater for a sea level rise of 0.8 m by 2100 (Qcoast2100, 2016). Minimum standards and guidelines for the plans are set out in an 8 phase Comprehensive Coastal Hazard Strategy (CHAS):

Commit and get ready

PHASE 1: Plan for life-of-project stakeholder communication and engagement

PHASE 2: Scope coastal hazard issues for the area of interest

Identify and assess

PHASE 3: Identify areas exposed to current and future coastal hazards

PHASE 4: Identify key assets potentially impacted

PHASE 5: Risk assessment of key assets in coastal hazard areas

Plan, respond and embed

PHASE 6: Identify potential adaptation options

PHASE 7: Socio-economic appraisal of adaptation options

PHASE 8: Strategy development, implementation and review

In essence, the CHAS requires councils to use the Queensland Government's coastal hazard maps to create current and future risk profiles for council assets such as foreshores, buildings, roads, water and sewerage infrastructure etc. as well as external stakeholder assets such as businesses and homes. Then using a combination of analysis techniques, the viability of potential adaption options is to be assessed against future costs of actions or inaction. If action is to be taken some time in the future, the CHAS should identify potential trigger points for when the approaching risk becomes unacceptable and action needs to be taken.

The order of preference for actions to be taken are given as:

- **Avoid the risk**
  Develop new urban areas elsewhere or construct new infrastructure in low hazard areas
- **Retreat from the hazard zone**
  Relocate or building setbacks
- **Accommodate the hazard**
  Increase resilience through retrofitting buildings and infrastructure
- **Defend from the hazard**
  Improved awareness and preparedness for extreme events.
  Construction and upgrades, hard engineering solutions such as buffers and seawalls

The Queensland Government's 2020 Climate Change report for Far North Queensland states that in the future, the Cairns region can expect:

- an increase in hot days, an increase in maximum temperature achieved on those hot days and a longer duration of warm spells (heatwaves)
- an increase in bush fire risk for inland areas
- variability in rainfall with the intensity of heavy rainfall and flood events likely to increase.
- tropical cyclones may be less frequent but the proportion of high intensity category 4-5 cyclones will increase.
- sea levels to rise by 0.8m above present-day levels by 2100.

(Qld Govt., 2020)

2.5.1 Cairns Coastal Hazard Adaption Strategy (CHAS)

In July of 2021, Cairns Regional Council (CRC) released its draft, 8 phase CHAS; "Our Cairns Coast: Adapting for the Future," for consultation. The document states the project aims to take a coordinated approach to coastal planning and adaption. The process starts with understanding the coastal changes (hazards) along the Cairns Regions 126km of coastline followed by identifying what this means for the Cairns community and the risks to businesses and infrastructure. Finally, the CHAS identifies general actions that will need to be taken over short, medium and long term time frames to avoid or reduce the impacts from our changing climate and sea level rise (Figure 2.16).

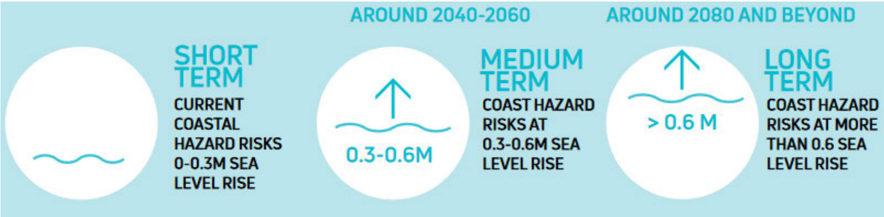


Figure 2.16: Time frames for Cairns CHAS (Our Cairns Coast CHAS 2021)

Figure 2.17: The vulnerable Cairns foreshore and central city area
(Cairns - The Rainforest City Master Plan)

The Cairns CHAS notes that less than 1% of the regions urban area is currently under threat from coastal hazards. However, by 2100 this will dramatically increase. With a 0.8m sea level rise, 67% of the city's retail/commercial area, 40% of the crucial tourist area and 25% of industrial areas are threatened with inundation during severe storms (Figure 2.17, Table 1) (Cairns Regional Council, 2021).

BASED ON A 0.8M RISE IN SEA LEVELS	Coastal erosion	Sea-level rise	Storm-tide inundation
Industrial areas	<1% (0.4 ha)	18% (252 ha)	25% (335 ha)
Retail and commercial areas	<1% (2 ha)	23% (81 ha)	67% (171 ha)
Tourism areas	3% (8 ha)	24% (44 ha)	40% (65 ha)

Table 1: Predicted impact of a 0.8m increase in sea levels on Cairns
Source: Our Cairns Coast CHAS (Draft) 2021

Cairns is very vulnerable to inundation from the ocean with significant parts of central city area only 2 m above mean sea level. Although the official storm surge map indicates the lowest areas of Cairns are 0.2 m above the highest astronomical tide, investigation by the author of this report shows that some key areas of central Cairns are already below the highest astronomical tide events and suffer regular inundation as a result of sea water coming up through the drains during king tide events. This highlights that significant parts of the city will be permanently within the tidal range, should sea level rise by 0.8 m (Figures 2.18(a-d)). Additionally, a small 1m storm surge, like what occurred during Cyclone Yasi (2011), during a normal king high tide would see the orange areas of Figure 18d flooded by around 0.8 m of water and red areas by around 1.8 m.

The Cairns CHAS notes the high population density of the inner-city suburbs that will be affected by this inundation. However, this is also where the key economic activity of the city occurs. The main commercial, retail and tourist areas, with hotels, restaurants, cafes and bars as well as the regional hospital, several schools, port/navy facilities and the airport are all in this area. Little action is cited in the Cairns CHAS to address the threat in the short term. In the medium-term council will take action to relocate or raise infrastructure and upgrade services to be resilient to inundation. In the longer-term council will investigate hard engineering options such as a detached break water, seawalls, tidal gates and a raised road around the city to form a levee.

Figure 2.18(a): Cairns greater city area (Google Earth)

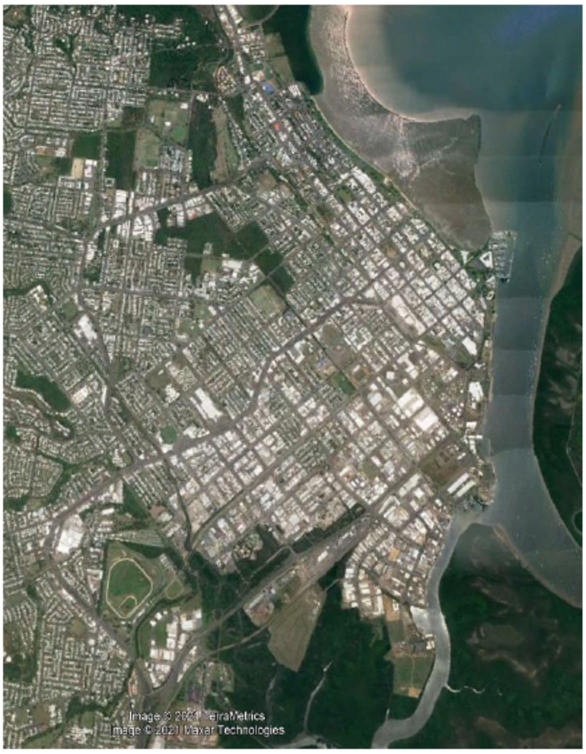


Figure 2.18(b): Cairns central city area (Google Earth)

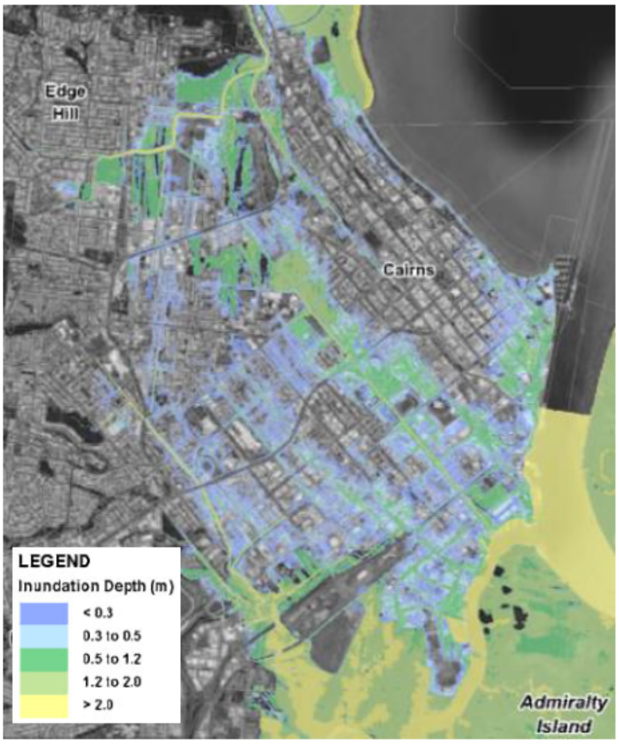


Figure 2.18(c): Cairns with sea level rise of 0.8 m
(CRC - Sea Level Rise Inundation Hazard)

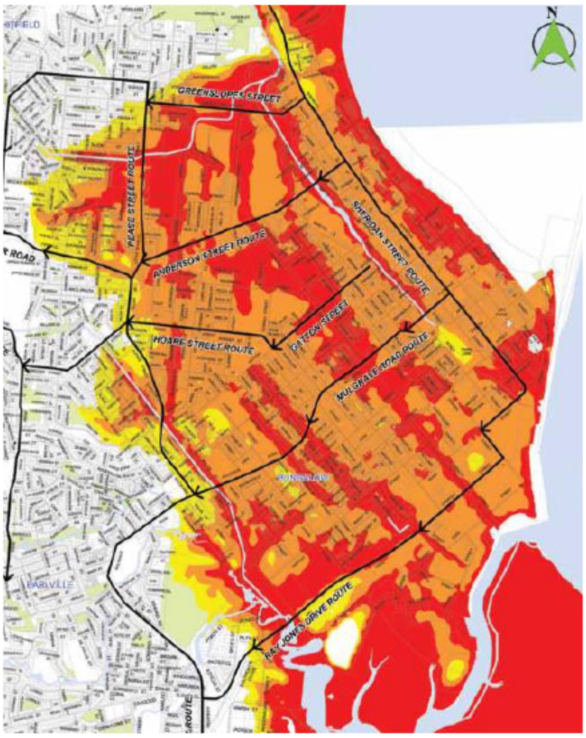


Figure 2.18(d): Cairns storm surge evacuation map
(CRC - Storm Tide Evacuation Guide)

Cairns storm surge map legend

Red Zone:	**2m**	above mean sea level	**0.2m**	above highest astronomical tide
Orange Zone:	**2-3m**	above mean sea level	**0.2-1.2m**	above highest astronomical tide
Yellow Zone:	**3-4.5m**	above mean sea level	**1.2-2.7m**	above highest astronomical tide

(CRC Storm Tide Evacuation Guide and Qld Govt tide predictions Cairns monitoring site)

2.6 Conclusion and knowledge gap

The degree of the threat to Cairns and other coastal cities from climate change and sea level rise is unprecedented. Saving our low-lying cities and adapting to this threat will become the greatest engineering challenge of our time. Cairns is one of the most vulnerable cities in Australia and will be amongst the first to be affected with some parts already experience inundation during king tide events. The city's tourist economy is dependent on being an attractive, fun, safe, nature-based destination. The very survival of Cairns and its economy is dependent on getting the response to sea level rise and cyclonic storm inundation right.

The threat from climate change and sea level rise has been accepted and incorporated into government and local council policy. Cairns Regional Council is well advanced with investigations and studies that identify the degree of the local problem, time frames and general actions to take. Recognising the problem and the need to develop developing plans, policies and procedures to reduce and manage the threat are important initial steps. However, no specific plans have yet been developed. There are no reports on strategies and technologies being implemented around the world and their suitability for being adapted to the localised conditions of Cairns. Practical engineering solutions have not yet been determined. This report explores these issues and addresses this gap in knowledge.

To identify possible solutions that may be applied to Cairns, the next chapter examines engineering solutions to coastal inundation that have already been implemented in other places around the world.

Chapter 3: Review of available technologies

3.1 Introduction

Coastal inundation is a common occurrence around the world. The Netherlands in particular, is well known for their ability to reclaim land and hold back the ocean. They have been doing this for hundreds of years. Japan suffered a major catastrophe in 2011 when a tsunami decimated many cities and towns. They have become expert at building seawalls. This chapter addresses the projects first objective of identifying possible solutions to protect Cairns from coastal inundation by exploring the broad lessons that can be learnt from these countries. The chapter then goes on to examine different types of seawalls, both temporary and permanent, to identify all options to be considered as possible solutions to protect Cairns from cyclonic storm surge and sea level rise.

3.2 Netherlands

When it comes to adapting to sea level rise and inundation from the ocean the best country in the world to analyse would have to be the Netherlands. Around 27% of the country is below sea level and around 50% lies 1 metre or less above sea level (Rosenberg 2019, Brilliant Maps 2017). The Netherlands is therefore exceedingly prone to flooding. Any breach of the walls by the North Sea would be disastrous. As well as being exceedingly strong, the walls also need to allow three large rivers (Rhine, Meuse and Scheldt) to flow out into the sea through the walls.

3.2.1 Original land reclamation method

The Dutch and their ancestors have been building dams and dykes to reclaim land from the sea for over 2000 years (Figure 3.0). The Frisians initially settled the Netherlands around 400 BCE, and were the first to create terpen's (Frisian word for village) on top of large earth mounds to protect from them from flooding. These were the first examples of lands being adapted in the area to protect from flooding (Rosenberg 2019).

Figure 3.0: The Netherlands in 1300 and today showing land from the sea (Lovenko 2018)

The devastating results of what can occur if the seawalls fail can be seen from an incident that occurred over 700 years ago. On 14 December 1287, in what became known as the St. Lucia floods, the North Sea breached the seawalls and over 50,000 lives were lost. Over the coming centuries the sea was pushed back by the Dutch. From the 1200's onwards this was aided by the use of windmills. An area would be sectioned off with dykes and the water pumped out using the windmills to give access to the fertile soil below. This method is still used today, although electric and diesel pumps have replaced windmills (Rosenberg 2019).

3.2.2 The Delta Works

The Delta Works (Figure 3.1) is a massive chain of modern flood protection structures that shield the Netherlands from the North Sea. This project came about after the North Sea flooded 9% of the country's farmlands and took 8,361 lives in 1953.

Figure 3.1: The Delta Works is a series of dams and other flood protection measures (Wiki Voyage 2022)

The Netherlands government created the delta commission to take charge of protecting the region from future flood related disasters. The immense project consisting of 13 dams in addition to a range of barriers, dykes, sluices, locks and levees was completed in 1997 at a cost of 5 billion dollars. The risk of flooding reduced to one in four-thousand years (Lovenko 2018).

The Oosterschelderkering barrier is the longest dam in the delta works. It stretches nine kilometres between the Schouwen-Duiveland and Noord-Beveland islands, and cost 2.8 billion euros to construct. The initial design was a fully closed, however this attracted significant public criticism due to its effect on the environment. As a result, a 4 km stretch now includes large sluice gates (Figure 3.2). The gates are 42 metres wide and normally open to allow natural tidal water flow. They can be closed within one hour in the event of extreme weather events. This prevents high tidal storm surges flooding the land, protecting not only the Dutch people but the marine environment inside the gates as well. The sluice gates are constructed between 65 concrete pillars ranging in height from 35 to 38.7 metres. The system for closing the sluice gates has been automated to remove the possibility of human error and occurs when the ocean height is expected to be 3 metres above regular sea level. The Oosterschelderkering has an annual running cost of 17 million euros, however this is considered a marginal cost in comparison to potential flood damage and risk to human life.

Figure 3.2: The 9 km Oosterschelderkering barrier includes 4 km's of sluice gates that allow natural water flow but can be closed during extreme storm events (Deltawerken 2022)

The Maeslantkering storm surge barrier (Figure 3.3) is one of the largest moving structures on Earth. It is located near the entrance of a major shipping lane and allows ships to pass through the coastal defences. The barrier consists of two floating gates, 22 metres high and an incredible 210 metres long. Steel V-shaped trusses strengthen the structure and transfer the water pressure to the world's largest mechanical ball joints at the point. These joints have a diameter of 12 metres and weigh 680 tonnes. Similar to the Oosterschelderkering, the gates are usually open but automatically close when sea levels are expected to be 2.6 metres above standard sea level. The gates are currently expected to close once every 10 years during the most extreme storm event. However, they have been designed to manage with a 1 m sea level rise at which point they will close an average of 3 times each year (De Bruijn *et al.*, 2022).

Figure 3.3: The 210 m Maeslantkering storm surge barrier allow ships to pass through the dam system into open ocean (Dutch Water Sector 2018 and Rijkswaterstaat 2022)

3.2.3 The Zuiderze Works

The Zuiderze works (Figure 3.4) is a land reclamation project inside the Zuiderze which is a large shallow bay. The Zuiderze was a good location for fishing and relaxing, however was prone to very large floods as the original dykes would often fail. On the 14th of June 1918 the Zuiderze Act was passed which had the three aims:

- To protected the area from the North Sea.
- Increase food supply by creating new farm land.
- Turn the current salt water bay into a fresh water lake.

The first step in the project was the construction of the 32 km long Afsluitdijk dyke (dam) to separate the inner bay from the sea. The dyke, completed between 1927 and 1932, is 7 metres high and 90 metres wide at the base. The inner bay became a fresh water lake and it became possible to incrementally reclaim more land inside the dyke. The top of the dyke also hosts a main highway that offers considerable time savings due to the direct route across the bay.

The four blocks of reclaimed land (called polders) total 1,620 km^2 (Britannica 2022). They were created by damming off sections of the lake and pumping out the excess water. Once the majority of water was removed, most of the remaining water was extracted using small ditches and channels. Reed plants were sown into the polders allowing for even more water to be removed and air to be added into the ground. Once fully dehydrated the polders became agricultural land although many towns have also been established on the polders.

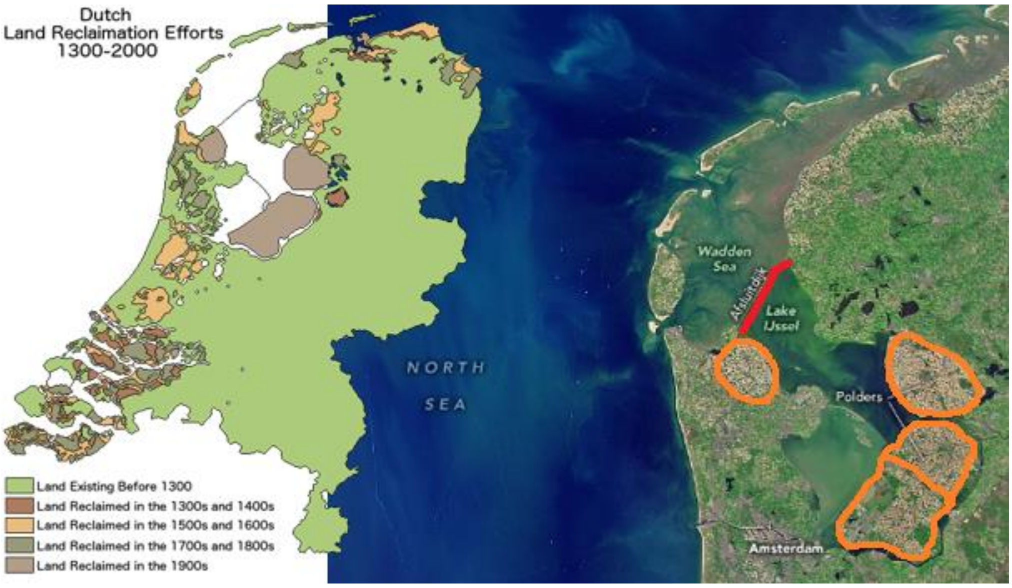


Figure 3.4: The Zuiderze Works started with the construction of the Afsluitdijk dyke (red) which then allowed 1,620 km^2 of land to be reclaimed (orange) (Brilliant Maps 2017 and Cassidy 2021)

After 90 years of successfully protecting the low-lying land around Amsterdam the Afsluitdijk dyke (Figure 3.5) is currently being raised by 2 m to protect against sea level rise. A layer of concrete armour blocks is also being laid on the seaward side to reinforce the dam against a one in 10,000-year flood. Heavy duty, 6.5 tonne blocks line the bottom 12 m band of the dyke whilst lighter and simpler blocks in the upper 17.5 m band are shaped to slow high waves. The design life of the newly renovated dyke is 100 years (Reina, 2021).

Figure 3.5: The 32 km long Afsluitdijk dyke is being raised by 2 m and reinforced with a layer of concrete armour (Tegg 2018 and Reina 2021)

3.2.4 Water management

During extreme weather events the various gates in the dykes are closed to prevent high tidal flows surging inland. However, this also prevents river and rain water from draining into the ocean. There must be sufficient capacity to hold the water that accumulates behind the dykes when the gates are closed until the excess water can be released after the storm event.

Large natural areas inside the dykes have been retained as water retention areas, however, these natural areas by themselves are not sufficient. Rotterdam is 80% below sea level and has adapted its buildings to help manage excess water. The city has over 100 acres of roof top gardens (Figure 3.6(a)) to capture and store 1.6 million gallons of rainwater to ease pressure on the city's drainage system. The city aims to increase this to 5 million gallons of rainwater by 2030. In addition to water storage, green roof tops have the added benefit of providing habitat for birds and insects which are otherwise normally limited in urban areas. Another positive benefit of replacing traditional heat absorbing rooftops and parking with green areas is the reduction in building and ambient temperatures by around 5 degrees. This has cut the cost of aircon in some buildings by up to 7% (Baurick, Wendland, Granger 2020).

Figure 3.6(a) and 3.6(b): Rotterdam reduces stress on drainage systems by storing excess storm water in rooftop green spaces and a sunken basketball court (Baurick, Wendland, Granger 2020 and Van Duivenbode 2022)

The water storage capacity of Rotterdam's rooftops is supplemented various public infrastructure projects. For example, the Watersquare Benthemplein basketball court and skateboarding ramps also serve as flood water retention areas (Figure 3.6(b)). This system by itself can store 2,182 Kilolitres which is then released into the city's drainage system once the storm event has passed (Baurick, Wendland, Granger 2020).

Key Learnings

- The scale and success of the Netherlands projects show that protecting Cairns from sea level rise is realistic and achievable.
- Coastal protection systems may be expensive but this cost is small in comparison to the loss of life and infrastructure if nothing is done or if what is constructed is insufficient and fails during severe weather events.
- The cost of protective systems can be reduced by dual purpose infrastructure e.g., highway on dyke replaces need for a bridge, basketball court also retains water.
- The water that accumulates on the land side of the wall must be managed by maintaining natural water soak areas supplemented with man-made retention areas.
- Construction of seawalls is also an opportunity to reclaim valuable land.

3.3 Japan's seawalls

Perhaps there is no better example of what is possible when building seawalls than Japan. The county has always been threatened by giant earthquake induced tsunamis. When the 2011 tsunami hit Japan's coastal cities, many were already protected by 6-10 metre high seawalls. Unfortunately, the 2011 tsunami was up to 15 metres, and even higher in some locations. The height of the tsunami varied in each location due to geographical features such as the slope of the ocean floor and the funnelling effect of bays and headlands. The 2011 tsunami simply flowed over the top of the seawalls (Figure 3.7). The walls did slow down the arrival of the tsunami, which allowed more time for residents to escape but did little to protect the coastal cities. Whole communities were destroyed leaving many thousands homeless and almost 20,000 dead (Nakahara 2013).

Figure 3.7: Tsunami wave crashes over the seawall in Miyako (The Guardian 2018)

Some seawalls failed completely. The strong currents created drag forces that scattered armour stones and blocks and the horizontal wave forces created large pressure differences between the front and back walls which caused some to simply topple over. Another common reason for failure was scouring of the walls foundations that occurred on the back side of the wall once it had been overtopped by the tsunami Figures 3.8(a-c).

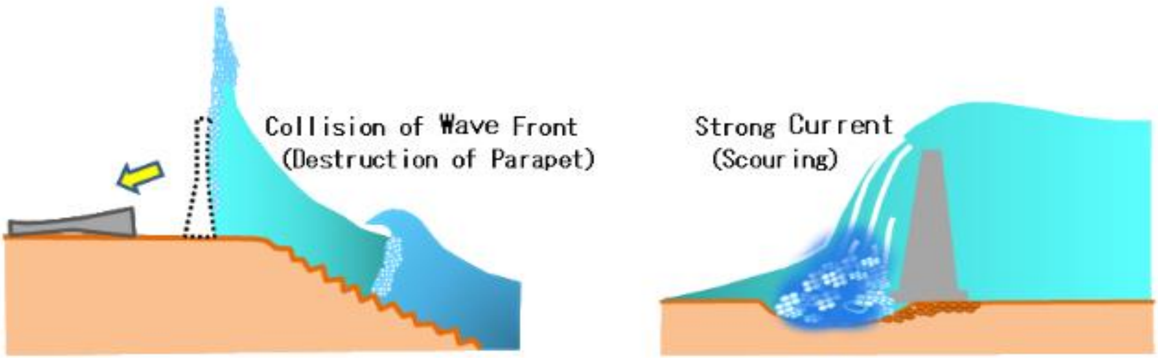


Figure 3.8(a): Some seawalls failed due to the force of the tsunami impact whilst others failed due to scouring of the foundations once the wall was overtopped (PARI 2011)


Figure 3.8(b) and 3.8(c): The seawall protecting the Fukashima Nuclear Power Plant disintegrated as soon as the tsunami hit and the failure of seawall at Ryoishi in Kamaishi (Daily Mail 2011 and PARI 2011)

The port of Kamaishi had the additional protection of a 2 km long, 6 m high breakwater at the entrance to the bay (Figure 3.9(a-b)). Before the breakwater, regular storms made the seas in the port choppy and loading ships difficult. Built in 2009 at a cost of A$1 billion and largely destroyed by the tsunami two years later, the Japanese Port and Airport Research Institute (PARI) found the breakwater reduced the height of the tsunami from 13.7 to 8.0 m and delayed the arrival by 6 minutes. This precious time allowed many to evacuate. Time to evacuate is often the key to surviving tsunamis. PARI considered it worthwhile to invest A$850 m to rebuild the breakwater (ABC FC 2021).


Figure 3.9(a) and 3.9(b): 2 km long breakwater entrance to Port of Kamaishi (ABC FC 2021)

The Japanese government's solution to the 2011 tsunami was to build higher, wider and longer seawalls. The result is an almost continuous A$17 billion, 400 km wall (ABC FC 2021). With a height of up to 14 m, the new wall is still below the height of the 2011 tsunami in some locations. Professor Tomoya Shibayama from Waseda University (ABC FC 2021) states the height of the wall is based on modelling a one in 100-year tsunami. He further stated it was not practical to aim for complete protection. Evacuation is still the first priority.

However, the new walls have been redesigned to survive being over topped. They will stay upright if submerged (Raby *et al.*, 2015). New features include:

- geotextile membranes to avoid leaching of infill material (Figure 3.10(a))
- reinforcement of toes on the landward side (Figure 3.10(a))
- widening of breakwater foundation rubble mounds (Figure 3.10(a))

- interlinkage/reinforcement of concrete block armour in seawalls (Figure 3.10(a)).
- improved foundation piles (Figure 3.10(b)).

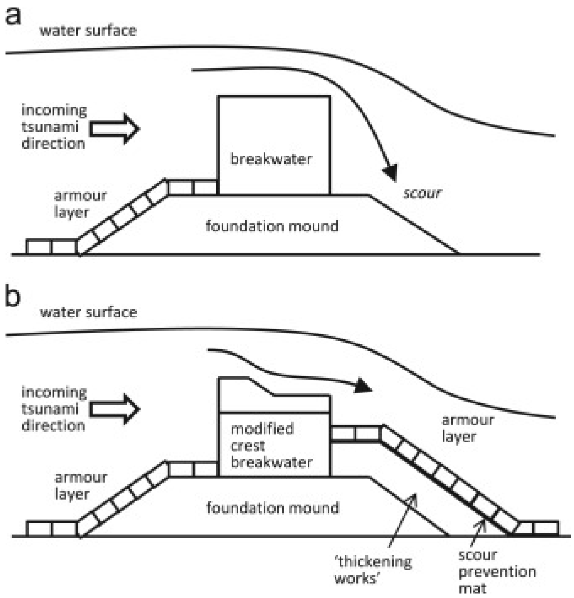


Figure 3.10(a): Example of original (a) and revised (b) seawall design (Source: Raby *et al.*, 2015)
Figure 3.10(b): Seawall at Noda has 25m foundations to make sure it will not fail if overtopped (ABC FC 2021).

In the years immediately after 2011, human lives were considered more important that the natural landscape. However, as time passed, many people started to question the **economic, social and environmental costs** of the walls. Traditional fishermen found the giant walls oppressive, like a prison. They felt a loss of connection with the ocean, cut off from their sea culture (Figures 3.11(a-f)). Some felt the wall that now protects them makes them more vulnerable as they cannot see what is happening to the ocean. Complacent residents may be reluctant to evacuate due to a false sense of security. Others talk about loss of access to the beach and the loss of the natural beach environment and natural coastal vistas. Some residents who initially welcomed the walls became critical, saying the money may have been better spent elsewhere, such as raising residential land, moving people to higher ground and new housing. Others question the expense of the walls when many areas directly behind have not been reinhabited - the walls protect vacant land and fields (Figure 3.12). (ABC FC 2021).

Figures 3.11(a) and 3.11(b): The seawall in the port of Miyako severs the towns traditional link with the ocean (Kyung-hoon 2018)

Figures 3.11(c) and 3.11(d): Seawalls destroy the natural look of the coast and sever human connection with the ocean (Asahi Shimbun 2021 and Huang 2022)

Figures 3.11(e) and 3.11(f): Small perspex windows have been incorporated in some walls in an attempt to give residents the opportunity to maintain some connection with the ocean (Kyung-hoon 2018)

Figure 3.12: Many areas directly behind the walls have not been reinhabited (ABC FC 2021)

The 2011 tsunami hit the city of Kesennuma hard. Whole neighbourhoods were destroyed and 1,200 lives lost. The central governments coastal protection policy called for seawalls and breakwaters sufficient to stop a Level 1 tsunami wave of up to 15 meters (100-200 year event). However, even with this level of protection, 75% of the area inundated in 2011 would still be under threat (Satoru 2021).

The plan was very divisive. Heated debate and protests continued for seven years. Many citizens were outraged when a 14.7 metre wall was built on nearby Koizumi Beach, one of Japan's "top 100 bathing beaches" (Figure 3.13).

Figure 3.13: 14.7 metre seawall on the popular Koizuimi Beach (Satoru 2021)

In Uranohama, Oshima, local residents were overwhelmingly against having an 11.8m wall. The residents accused the local prefecture of acting without regard for the people who lived in the area. Oshima is known for its natural beauty and charm and the wall would destroy this. After much disagreement and confrontation, community stakeholder groups and local authorities started working collaboratively and an alternative plan evolved (Satoruon 2021):

- A 7.5m seawall to be built 30 metres back from the water's edge.
- The wall on the bay side would be hidden under earth and grass.
- The area behind the wall would be back filled to the same height as the wall allowing a visitor complex to be built on top of the wall.

The natural look of the area and ocean views were maintained (Figure 3.14).

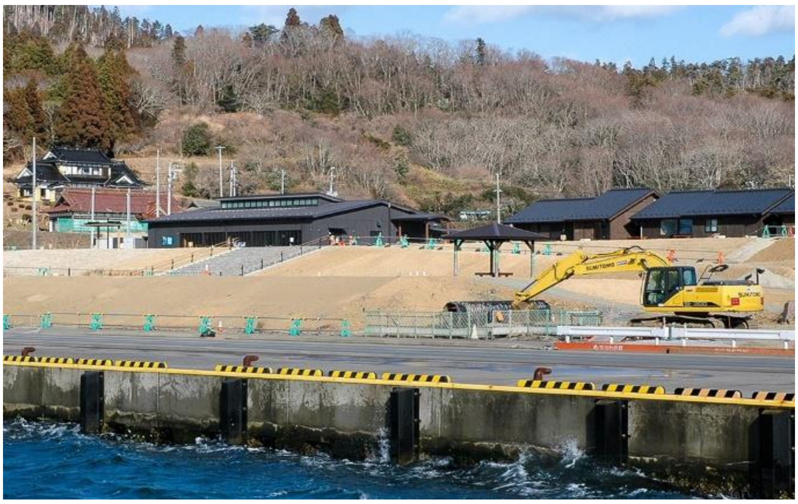


Figure 3.14: A 7.5m seawall in the fishing Port of Uranohama Oshima being covered in soil to maintain the natural look of the area (Satoru 2021)

Other Kesennuma communities started to send their plans back for modification. Naiwan is an inner harbour shopping, entertainment, port and tourist area. Residents rejected the proposed 6.2 metre concrete wall and pushed for a more creative solution (Satoru 2021). Instead, a 4.1 metre concrete wall was constructed. An additional 1m flap is automatically raised by water pressure during a tsunami (Figure 3.15(a)). Although an expensive option, Naiwan's view of the ocean was successfully preserved. Further along, a 5-metre concrete wall was integrated into the waterfront townscape. Restaurants, cafes and public facilities were built on top of the structure. The wall blends in with other construction and an abundance of ocean views has been achieved (Figure 3.15(b)). A less developed part of the shoreline was left completely wall free to maintain the broader natural look of the area.

Figure 3.15(a): Naiwan seawall has an additional 1m flap (red) which is automatically raised by water pressure in the event of a tsunami (Satoru 2021)
Figure 3.15(b): Naiwan harbour with shopping and tourist facilities built on top of the wall to maintain ocean views and connection with the sea (Good Design 2019)

Key Learnings

The scale of the Japanese project shows what can be achieved in a short 10-year period, when there is focus, commitment and cost is not the main factor. It puts the requirements for protecting Cairns into perspective and shows it is very achievable. The many failures of the pre-2011 seawalls show the importance of properly engineered foundations and armour that can cope with the rare events when walls are over-topped. This includes the effects of scouring and sea water accumulating behind overtopped seawalls creating pressure on the back of the walls causing them to collapse towards the ocean.

The most important lesson is perhaps what has not been done well in the Japanese example. In the race to complete projects, little consideration was given to social and environmental impacts. Only in later projects, and then only after years of division and disagreement, did authorities start to consider the views of the residents who live in the area and the effect of any solution on their livelihoods and lifestyle. Gaining acceptance and support requires listening to the local population and including them in a genuine consultation and development process.

3.4 Machans Beach, Cairns

Machans Beach is a Cairns suburb located about 7 kilometres north of the CBD. It is an excellent example of the threat that much of Cairns faces. Cairns is built on the sandy swampy soils of Trinity Inlet while Machans Beach has been built on the sandy soils of the low-lying Baron River delta. The foreshore has always been subject to erosion but the king tide event of 1966 caused the complete collapse of the foreshore (Figure 3.16(a)). In response a rock wall was completed in 1968 and the foreshore restored (Figure 3.16(b)).

Figure 3.16(a): King tide erosion at Machans Beach in 1966 (Harwood 2022)
Figure 3.16(b): Rock wall constructed in 1968 to protect from further erosion (Harwood 2022)

The purpose of the rock wall was to prevent the shoreline from retreating further. However, overtime, the impacts of cyclones and tides undermined the seawall. Five cyclones impacted the wall from 2005 to 2014 (Cyclones Ingrid, Larry, Monica, Yasi and Ita). Although Machans Beach did not suffer a direct hit from any of these cyclones, the steep seawall became unstable, with many rocks no longer supported from below and in danger of falling (Figure 3.17) (Queensland Coast 2014). The destruction of similar seawalls located in towns further south of Cairns by Cyclone Yasi in 2011 showed that these types of seawalls cannot stand up to a direct hit from a severe category 5 cyclone.

Figure 3.17: Old Machans Beach seawall. Badly eroded at the water's edge, with unsupported rocks that are close to collapse (Queensland Coast 2014)

The Cairns City Council acknowledged the wall as dangerous and at risk of failure during significant storm events. In 2014 they commenced to construct a 1,300 metre, engineered seawall, in front of the old wall. The new seawall (Figure 3.18) was to designed to be more stable with larger rocks and a shallow, flatter rock face. The wall is much thicker and wider with the rock batter and toe apron 17 metres further out to sea. The opportunity was also taken to reclaim an additional 6 metres beyond the crest of the existing wall to create a narrow foreshore (Engineers Australia 2014).

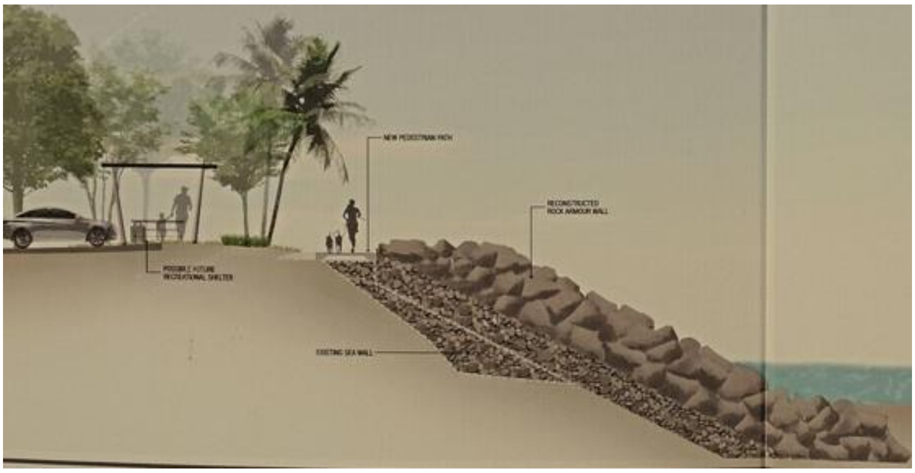


Figure 3.18: New engineered seawall at Machans Beach (Queensland Coast 2014)

The new seawall was constructed in layers in front of the old wall (Figure 3.19). Small stones of around 150 mm form a base layer which was covered by geotextile. The geotextile layer gives added strength to the wall by preventing finer material being eroded out from behind the wall by the movement of tides and waves. Loss of fine material creates deep holes in the wall structure. A layer of rocks the size of a wheel barrow bucket, which is around the size of the rocks on the original seawall, has been placed on top of the geotextile followed by a layer even larger rocks, some in excess of 2 metres (Queensland Coast 2014).

Figure 3.19: Machans Beach seawall and land reclamation (Cleary 2015)

To construct the seawall and reclaim land, a temporary road was built out into ocean to allow access and protect the works from incoming tides (Figure 3.20). As the road was constructed, mud was dug out and replaced with large rocks to create deep footings (the toe). The shoreline was then built to reclaim an additional 6 metres of land. Rock layers were then laid down and the temporary road removed. (Queensland Coast 2014).

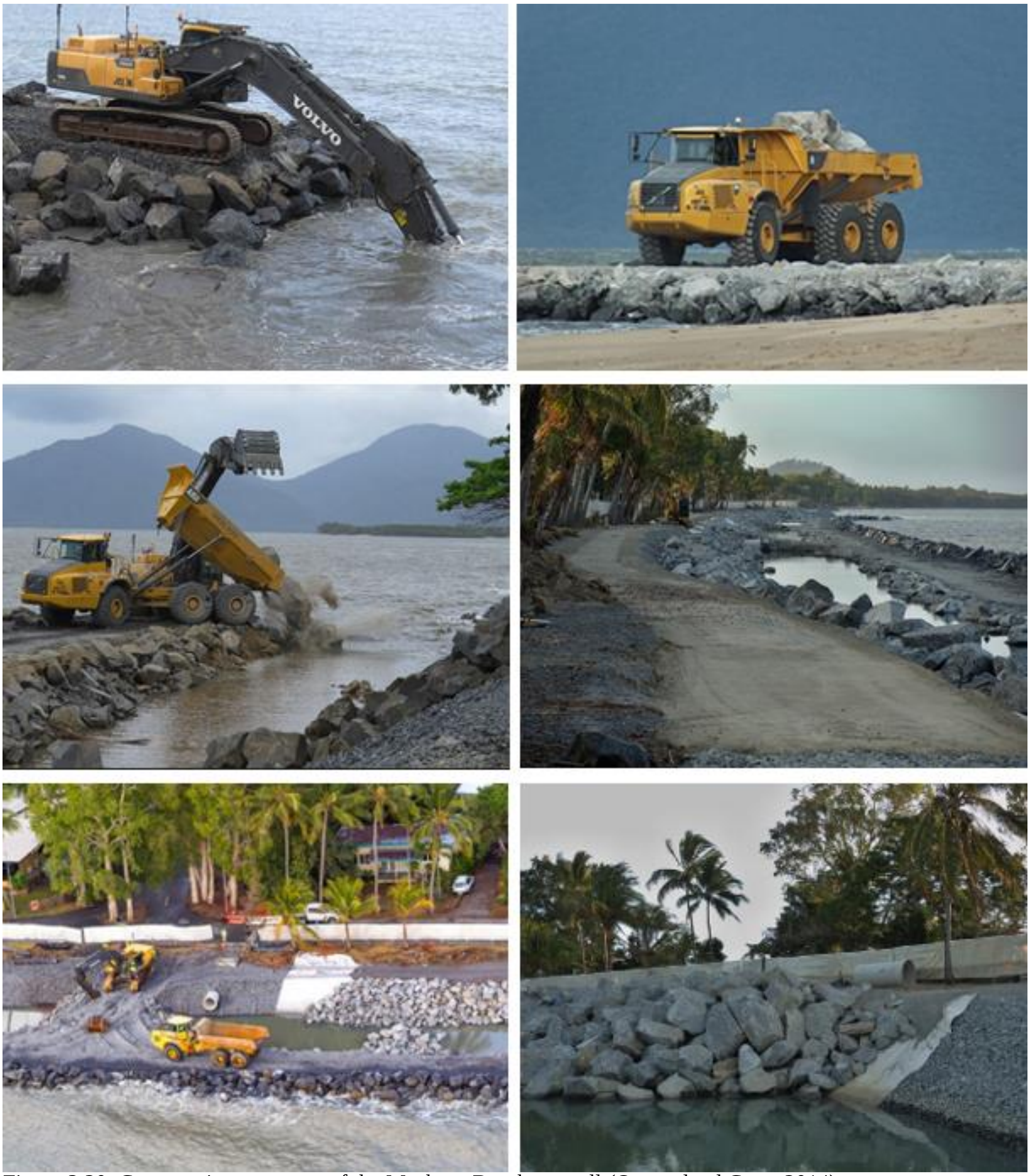


Figure 3.20: Construction sequence of the Machans Beach seawall (Queensland Coast 2014).

The project reclaimed up to 6 metres of land allowing for a pleasant foreshore recreation/path to be created at the top of the wall (Figures 3.21(a-b)).

Figures 3.21(a) and 3.21(b): Machans Beach seawall with new reclaimed foreshore walkway
(Cleary 2015 and O'Donoghue 2022)

Inspection of the site shows the reclaimed land is higher than the residential blocks on the other side the road. In addition, the wall has been raised about 0.5 metres above the reclaimed land, indicating the council took the opportunity to create additional protection against storm surge and sea level rise. The author's observations is that the way the wall is constructed leaves opportunity to increase protection in the future if required. As the top of the wall is so broad it would not be difficult to increase its height with additional rocks. Alternately, the reclaimed land could be raised further and a short concrete wall constructed on the ocean side of the path. The author notes that the beach remains at low tide and has not eroded away. The toe of the wall is still well below beach level. Some movement in rocks at wave level was observed and the wall is yet to be tested by a Cyclonic storm surge. Due to the thickness of the wall, and deep foundations, some movement in the rock armour is not likely to be a problem. However, this may indicate some repairs may be required in future decades.

Key Learnings

The 1.3 km Machan's Beach project offers great insight into how protection of the 3.0 km Cairns Esplanade might be achieved. It highlights that the building of a seawall is also an opportunity to reclaim land. Although a simple rock wall protected Machans Beach for 45 years, it was not fully tested by a direct hit by a cyclonic storm surge during this time. Simple rock walls like the 1968 version of the Machans Beach seawall do not offer sufficient protection. The Cairns Esplanade requires a fully engineered seawall solution with deep foundations. Any solution should also allow for future alterations, such as the opportunity to increase height, as the threat of sea level rise increases.

3.5 Thames Barrier (London, UK)

London is a city of 9.5 million people (Macrotrends 2022) and the capital city of the United Kingdom. The greater city area has been built on the flood plain of the Thames River. The Thames Barrier is the world's second largest flood defence barrier and protects 125 km^2 of central London including 1.42

million people and 321 billion pounds of property and infrastructure from flooding caused by exceptionally high tides and storm surges. The barrier came about after floods in 1953 claimed 307 lives and caused an estimated 50 million pounds damage (5 billion pounds today) which led to a dramatic rethink on how to protect London from floods (Royal Geographical Society 2022).

The Thames barrier has been operational since 1982, cost 500 million pounds (1.6 billion pounds today) and spans 520m of the river. It consists of 10 gates that can be closed to prevent tidal floods surging up the Thames River and flooding central London (Figure 3.22). The Thames Barrier has been closed over 200 times since it became operational (UK Environment Agency 2021).

Figure 3.22: The Thames Barrier with gates closed (UK Environmental Agency 2021)

The gates normally sit on the bottom of the river (Figures 3.23(a-b)) which allows river traffic to pass over top. When an impending flood event, such as a king tide, is identified, the gates are slowly rotated whilst still at low tide. This creates a large reservoir behind the barrier for the river to fill without flooding London. High tidal flows and storm surges are unable to flow up river past the barrier and into central London. The gates are left shut and the river water is held until the tide turns. As the tide reduces below the level of the held river water, the river flow is slowly released.

Each gate has 4 separate motors, 3 connections to the UK power gride and 3 separate diesel generators which can operate the entire barrier if the UK power grid is shut down. The large number of contingency plans are essential to ensure that failure of the barrier doesn't occur. The piers holding the barriers are constructed out of cement with the steel gates covered in a sacrificial toping to increase life span and protect from rusting. The barrier was designed in 1970 with a 60-year life span. However, simulations suggest it will last another 40 years which means the barrier will likely be in use until 2070. The very long-life expectancy is due to the barrier being designed with a large margin on safety. The barrier requires a full-time team to monitor systems and test the gates twice a month to ensure they are functioning correctly (UK Environment Agency 2021).

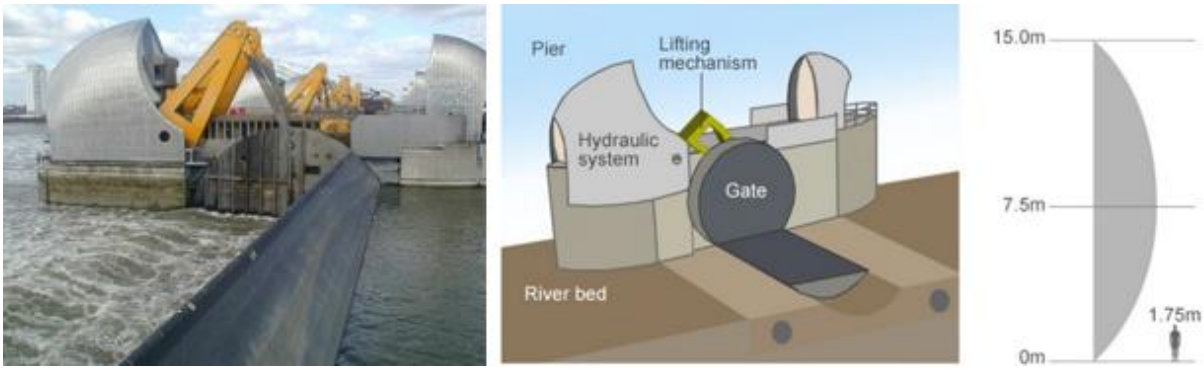


Figure 3.23(a) and 3.23(b): The lifting mechanism rotates the gate from the bottom of the river to its closed position (Bennett-Ness 2021 and De Castella 2014)

Key Learnings

Examining a large-scale project like the Thames Barrier is useful to show that rivers as large as the Thames can be successfully blocked for short periods to prevent tidal storm surges coming up the river and flooding the city. Cairns is in a similar situation. The Thames Barrier demonstrates what is possible and provides an example of how small-scale version of these gates could be built on the drainage outlets in Cairns to prevent cyclonic storm surges inundating the city.

3.6 Geodesign temporary flood barrier

Eastern Australia's unprecedented flood event over February and March 2022 impacted a vast area from south-east Queensland down to Sydney, and according to Major-General David Thomas, head of the Defence Force's flood-recovery task force, resulted in the loss of 22 lives (Moore 2022). However, one city was less affected that it otherwise would have been. Maryborough, is a flood prone city of 27,299 (id community 2022) about 250 kilometres north of Brisbane. In 2017, the local council invested about $6 million in a temporary Geodesign flood barrier (Figure 3.24) after floods in 2011, 2012, and 2013 caused an estimated $43 million in damage (Marie 2022).

Figure 3.24: Temporary flood wall successfully holding back flood waters in Maryborough (Marie 2022)

The portable flood barrier is produced by Swedish company, Geodesign Barriers Ltd. It is constructed from steel and aluminium to create a robust and flexible barrier capable of being constructed by one man without tools. The barrier comes in a range of sizes up to 1.8m (Figure 3.25) and adjusts to local topography providing a flexible solution that is suitable for a wide range of situations. The barrier can be constructed in a reasonable timeframe and then deconstructed for storage in a compacted form. The 1.8m Maryborough barrier was constructed by a team of 30-40 people in around 6 hours. The weight of the water pushing down on the angular face of the barrier is enough to seal the system against the ground (Marie 2022).

Figure 3.25: Three versions of the flood barrier are available up to 1.8m (Geodesign Barriers 2022)

The benefits of the system are:

- Available in different heights.
- Flexible system that can be adapted to local topography.
- Portable and easy to set up.
- Compactable and easy to store.
- Low cost.

The disadvantages of the system are:

- Not practical to construct long sections.
- Could cause worse inundation to buildings caught on wrong side of the barrier.
- May only be suitable for calm water flooding and may not be suitable for inundation from cyclonic storm surge with wind and waves.
- If flood events are regular a more permanent solution would be preferable.
- Labour intensive and time consuming to set up and pull down.

3.7 Flow Defence

Flow Defence is an Australian company that produces self-activating flood barriers that automatically rise in the event of a flood. The flood barrier is positioned underground in an “open state” which allows vehicles and pedestrians to travel over the top. As the water level rises, it flows through a grate in the defence system and into a small water storage area. As it fills, the buoyant wall is automatically lifted to ground level (Figure 3.26). Once fully deployed a seal is created due to hydrostatic vertical and horizonal forces.

The self-contained flood wall can be applied to a wide range of situations including driveways, carpark basement ramps, walkways and stairwells. A submersible pump is included in the system to drain the water storage area after the event or when needed. The barrier comes in a range of sizes up to a maximum height of 2.4m (Flow Defence 2022).

Figure 3.26: Flow Defence comes as a self-contained unit that is automatically raised by floodwaters entering the systems water storage tank (Flow Defence 2022).

The benefits of the system are:

- It is self-contained and hidden away so does not affect the look of the location.
- A small footprint that is less than one metre wide at its maximum configuration.
- Minimal earth works are required at installation.
- Once installed, it is always ready for a flood event – it is a permanent solution and no preparation work is required to activate the wall.

- As the unit automatically operated by rising water, no external power source is required, a significant advantage in the event of power loss during storm events.

The disadvantages of the system are:

- Compared to other flood wall options it is more expensive as it requires earthworks at installation.
- The only examples of this flood wall in use are over expanses of several metres. No examples are provided over longer spans indicating it may not be structurally sound enough to support water force over longer distances.
- The height of the wall cannot be upgraded without total replacement. The concrete foundation would need to be removed and deeper earthworks undertaken to support a larger sized wall.

3.8 NoFloods flood barrier tubes

NoFloods flood barrier (Figure 3.27) is a light weight highly adaptive temporary solution for flood prevention. The barrier is a simple water filled, high strength, flexible tube that supplied by Bluemont Pty Ltd in Australia. A 1 km length of this modern alternative to traditional sand bags can be rapidly deployed in less than 4 hours with only 4 people and a small truck (Bluemont 2022).

The flood barrier is very simple to set up:

- Roll out the tubes.
- Connect the tubes to the water terminal.
- Fill the tubes with air to stabilise and allow for adjustments (a small air blower can fill 100m in 4min).
- Pump water into the tubes while releasing the air.

Figure 3.27: Examples of the NoFloods mobile flood barrier in use (Bluemont 2022)

The barrier comes in 50, 100 and 200 metre lengths. The standard 125 cm twin tube model is able to retain water to a depth of 80 cm. When combined with a stackable triple tube, protection up to 120 cm in depth can be obtained (Figure 3.28(a)). Once filled, the weight of the water forms a tight seal against the ground and is suitable to protect against inundation from the sea (Figure 3.28(b)).

Figures 3.28(a) and 3.28(b): The system can be stacked to increase height and is suitable to protect from inundation from the sea (Bluemont 2022)

The barrier roles are attached to a frame that can be placed on the back of a truck or carried by a large fork lift (Figure 3.29) which allows for quick deployment and greatly reduces the man power needed for setup.

Figure 3.29: The barrier can be quickly deployed by a small truck or fork lift (Bluemont 2022).

The benefits of the system are:

- Designed to keep the sea at bay, suitable for king tide events.
- The standard model protects against up to 80 cm of flood water.
- It is quick and easy to set up, with the use of a vehicle or other machinery.
- It can be configured in a range of formations very quickly.
- It can cover very long distances in comparison to other flood mitigation options.

- It is light weight, reusable and can be easily stored in condensed rolled up configuration.

The disadvantages of the system are:

- It is a temporary solution only.
- It requires a large water source nearby and pumps to fill the tubes.
- To obtain the maximum protection height of 120 cm a twin tube model must be stacked on a triple tube model.
- The system's ability to stand up to impact of larger waves or waves driven by cyclonic winds is uncertain.

3.9 Seawalls

Seawalls are barriers that aim to protect coastlines from erosion and inundation from the sea (Figure 3.30). A seawall needs to be properly engineered and built to withstand the impact of ocean waves and severe storm events. Seawalls typically have a design life of 25-100 years. The design and cost of each wall depends its size, design life and the severity of the events it is designed to withstand. The design performance of a seawall should protect against the most common reasons that seawalls fail:

- Erosion of the armour layer – the concrete or rock face of the wall must be able to withstand the impact of waves without being swept off the structure.
- Undermining – wave action can scour and wash away the underlying base (toe) of the structure, causing it to slip or even collapse into the ocean.
- Wave overtopping – waves that wash over the top of the wall scour and wash away the material immediately behind the wall. This reduces the integrity of the structure and can cause damage or collapse.

(Coastal Engineering Solutions, 2022)

Figure 3.30: Repeated impacts from waves erode the shoreline (Surfrider 2022)

3.10 Construction materials

Seawalls are made out of a wide variety of materials (KE Braza Construction, 2022) including:

3.10.1 Timber

Timber seawalls offer low initial costs and ease of installation. This type of material will perform well in inland waterways. However, strong ocean waves can cause the wall to deteriorate and over time the walls are prone to rotting. Timber is not recommended for ocean facing seawalls.

3.10.2 Steel

Steel is also a common material for seawalls and can be installed at any height. The material is extremely strong in comparison to other materials available but has a high initial cost. Additionally, a protective coating need to be applied periodically as a sacrificial layer to avoid deterioration from corrosion. If properly maintained steel can last over 25 years.

3.10.3 Aluminium

An aluminium seawall shares a lot of properties with steel, both lasting around 25 years. However due to it being more light weight it isn't recommended for use in high seawalls or in low pH water which can lead to corrosion.

3.10.4 Vinyl or plastic

Vinyl or plastic is a newer material used to make seawalls. The colour is customisable making it able to aesthetically fit into the surrounding location. They may have a life span of over 50 years but have limitations as to what situations they are suitable. They also have height limitations so are really only suitable for small seawalls with minimal impacts from tides and storms.

3.10.5 Rock

Along with concrete, rock is one of the most durable materials used for seawall construction. Rock and concrete are therefore the most common materials for constructing seawalls. Rock has the advantage of being cheaper but is not available in many areas.

3.10.6 Concrete

Concrete is one of the most durable and adaptable materials used for seawalls construction, having the capability to last decades and requiring minimal or no maintenance. Concrete constructed seawalls are very resistant to wave impact and are able to be moulded in many different configurations. This flexibility makes it the material of choice in many locations.

3.11 Types of seawalls

The term seawall usually refers to a solid vertical structure whilst a revetment is a sloped rather than vertical seawall (Komar, 2011). Within these two general categories there are many different types and variations of seawalls, all of which have their advantages and disadvantages.

3.11.1 Bulkheads

Small vertical walls known as bulkheads (Figure 3.31) are generally more of a retaining wall. They are usually built along sheltered waters along rivers, estuaries and lakes (Dugan *et al.*, 2011). They are designed for small, infrequent waves and are most commonly seen in front of shore facing homes and harbours where they provide stability in areas where ships are loaded and unloaded.

Figure 3.31: Small bulkheads protect against erosion in sheltered areas (Thaler Contracting 2022)

Advantages:

- Small, cheap easy to build.
- Often built by individual homeowners.

Disadvantages:

- Usually small in size.
- Suitable only for sheltered waters with small, infrequent wave action.
- If overtopped, the ground behind the wall can be eroded away. The build-up of water behind the wall can cause it to collapse outwards.

3.11.2 Gabions

Gabions consist of rocks placed in metal caging. The cages are stacked to create a wall. They are most commonly seen on road embankments as retaining walls or to prevent erosion on river and creek banks. Occasionally, they are also used as seawalls (Figures 3.32(a-b)). Gabions are a very cheap solution and can even be made out of recycled materials i.e., old railway lines (Figure 3.32(b)). The gaps in the rocks are very good at absorbing wave energy and preventing slopes and cliffs from eroding and being undercut. Compared to other options they are less attractive as the cage tends to fit poorly into the surrounding environment.

Gabions last many decades when not directly impacted by sea water. Salty sea water corrodes the metal cage and wave impacts cause the cages to break (Figure 3.33(a)). However, even if the lower cages break, the wall will still continue to function for much longer (Figure 3.33(b)). Nevertheless, in extreme situations, when directly impacted by waves, gabions should be regarded as temporary structures for no more than 2 years (Cherkasova, 2019).

Figure 3.32(a) and 3.32(b): Gabion walls made out of stacked wire cages and recycled railway lines (Aathaworld 2022 and Coasts 2022)

Figure 3.33(a) and 3.33(b): Wave action can destroy a gabion cage within a couple of years (Cherkasova 2019).

Advantages:

- Very inexpensive.
- Easy and quick to construct and dismantle.
- Long life – when not directly impacted by sea water.
- Cheap short term seawall solution – whilst awaiting something more permanent.

Disadvantages:

- Cages are unattractive.
- Short term solution (2 years) when used as a seawall impacted by waves.
- May require regular repair/maintenance after severe storms.

3.11.3 Vertical Seawalls

Seawalls, like bulkheads, are vertical structures but differ due to their size and purpose. Seawalls are designed to resist the high impact forces from waves regularly crashing against them. Seawalls are therefore much more significant structures engineered to withstand the severest storm event. Additionally, they have a very small footprint so are an ideal solution in many locations where space is limited (Hosseinzadeh et el., 2022).

Unless the wall is built very high, it can be overtopped by the wash that is created as the wave crashes against the wall during severe storms. This can still cause damage to the infrastructure behind the wall. (Figure 3.34). Seawalls are built tough to absorb the wave energy. However, vertical walls cause waves to bounce back off the wall. The reflected wave creates a lot of turbulence in front of the wall which can result in sediments being washed away from the wall and the beach to erode over time (Hosseinzadeh et el., 2022). Scouring at the toe of the wall can threaten the stability of the wall and cause it to catastrophically fail (Komar, 2011). Deep foundations and rip rap rocks placed at the foot of the wall may help to overcome this problem.

Figure 3.34: Waves crashing over the Dawlish concrete seawall (Network Rail 2021)

Advantages:

- Very effective at protecting shorelines from erosion.
- Easy to design and construct (depending on location).
- Narrow construction with a small footprint.
- If property engineered, capable of resisting wave action and severe storms.
- Durable, tried and tested over many decades.

Disadvantages:

- Need to be properly designed/engineered and very costly to construct.
- Large, unattractive structures when compared to natural shorelines.
- Reflect wave energy back towards the sea creating turbulence and backwash which can scour or erode the sand immediately in front of the wall.
- Wave run up and the splash from waves crashing against the wall can overtop the wall causing damage and erosion on the land side of the wall.
- Can catastrophically fail during severe storm events - difficult and expensive to fix.
- Can alter the pattern of waves, currents and sediment movement along the beach. Over many years this can slowly erode and lower the level of the whole beach.
- Increased erosion at unprotected areas at both ends of the seawall.
- Destroys the natural shoreline, poor ecological properties.

3.11.4 Curved Seawalls

Historically, seawalls have been large flat walls. However, the design can be improved with a curved rather than flat wall or a curved section at the top of flat vertical wall. A curved wall reduces the risk of over topping by breaking the wave energy up and redirecting the wave and any wash back into the ocean. The redirection of wave energy results in lower stress magnitudes on the wall. A curved wall performs better during severe load events and suffers less scouring at the base of the wall. The addition of steps at the base (Figure 3.35) helps break up waves prior to impacting the wall and further protects the base of the wall from scouring (Hosseinzadeh *et el*., 2022). These types of walls are the gold standard of seawalls.

Figure 3.35: Curved seawall with stepped base at Southwold UK (Horn 2008)

All seawalls eventually fail. As they do, engineers learn from each failure and seawall design is constantly being improved. In 2014, the old seawall protecting the railway line at Dawlish in the UK started to crumble due to the impact of crashing waves in a severe storm. Once breached the gap quickly grew and the area behind the wall rapidly eroded away. (Figure 3.36).

Figure 3.36: Storm waves caused the old Dawlish seawall to crumble (Channel 4 2014)

The new wall (Figure 3.37) is made out of 9 ton concrete blocks that are shaped like Lego blocks to lock into each other. Stability is provided by deep, strong, reinforced concrete foundations and scour protection. Concrete piles, 9 metres long, were driven deep into the ground. The top section of each pile was drilled out to accommodate 57 mm thick steel reinforcing bars that extend all the way to the top of the wall through hollow sections in the concrete blocks. The hollow sections were then infilled with concrete to create one solid wall. The wall was then topped with L section recurve units that reflect any wave wash back into the ocean. The wall has a design life of 100 years (BAM, 2022).

Figure 3.37: Construction of new Dawlish Seawall (BAM, 2022)

Advantages:

- Highest level of protection against the most severe wave impacts.
- Redirects wave up and back out into the ocean.
- Diverts the energy of the wave – causes less disturbance in the ocean so there is less scouring when compared to a vertical wall.
- Long life with no maintenance for many decades and up to 100 years.

Disadvantages:

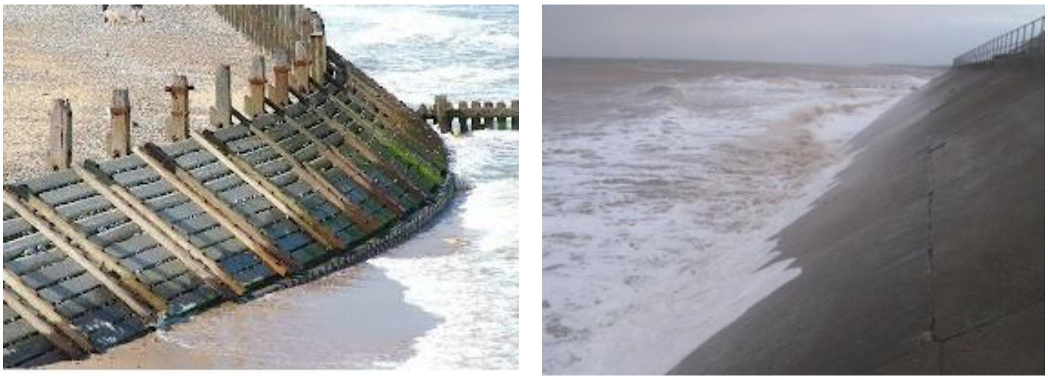
- Very complex walls with significant design and engineering required.
- Difficult and time consuming to construct.
- Very expensive wall.
- Can succumb to rapid and complete failure.

3.11.5 Revetments

Revetments are a type of seawall with a sloped rather than vertical face. Unlike vertical seawalls, which take the full brunt of the wave energy, the slope of revetments is designed to break up and reduce the force of the wave impact. Because of their gradual slope they require much more space. A revetment that is 6 metres high, with a slope of 2:1, will have a footprint of 12 metres (Dugan et al., 2011) compared to a seawall which may only occupy 2 metres.

Revetements are covered with a top armour layer to prevent wave impacts washing the wall away. Historically, the top armour layer may have been wood or a concrete slab (Figures 3.38(a-b)).

However, it is now more common for the armour layer to be made from large rocks or prefabricated concrete blocks.



Figures 3.38(a) and 3.38(b): Revetments made of wood and concrete (Gordon 2022 and Coasts 2022)

3.11.6 Rip Rap

A Rip Rap revetment is a sloped seawall made from armour rocks that face the oncoming waves. In more sheltered locations the rocks may be quite small (Figure 3.39(a)). However, in more severe conditions the outer layer of rocks need to be much larger (Figure 3.39(b)) to resist the force of waves crashing against them. Layers of smaller rocks under the outer armour layer prevent water surging through the gaps in the rocks and washing away the underlying soil or sand.

The semiporous surface of rip rap revetements dissipates some of the wave energy, leaving less to be reflected back into the ocean. This reduces turbulence which results in less scour and beach erosion. Although rocks can be dislodged by repeated wave impact, the wall is unlikely to succumb to rapid and complete failure like vertical seawalls (Komar, 2011). In addition, rip rap revetements are less complex and easier to install and offer a more natural look for a shoreline.

Figures 3.39(a) and 3.39(b): Small and large boulder rip rap walls (Kass 2022 and Vikellis 2022)

Advantages:

- Cheaper than seawalls to construct but still quite expensive.
- Cheap and easy to maintain.
- Rip rap rocks have a more natural look so are more appealing to the eye.
- The rough, semiporous rock face dissipates wave energy, resulting in less scour when compared to vertical seawalls.
- Sloped revetments tend to reflect less wave energy back into the ocean so are less prone to eroding the beach.
- Sloped revetments are less likely to suffer complete failure during severe storms and any damage can be easily fixed with the addition of more rock.

Disadvantages:

- Still need to be properly engineered to suit conditions.
- Require a large footprint – not suitable where space is limited.
- Not suitable if rocks not available.
- Rocks can move over time and become unstable – may not be safe to climb on.
- Needs occasional maintenance and rocks replenished from time to time.

3.11.7 Tetrapods

Tetrapod is a generic name for multi-legged pre-cast concrete blocks. They come in a variety of sizes and shapes and are similar to rip rap in that they are placed randomly in a rubble mound. The blocks interlock and due to their weight and shape the can remain stable during the most extreme storms. The large gaps between the tetrapods (Figure 3.40) create a porous barrier that dissipates the force of the incoming wave by allowing the water to flow around them (Bright Hub Engineering 2009).

Figure 3.40: Tetrapod mound wall (Southern Dredging & Marine 2022)

Advantages:

- Allows water to pass through and around them.
- Very good at dissipating wave energy.
- Most resilient in severe storm events.
- Can be combined with other materials.
- If tetrapod becomes damaged it is easy to replace.

Disadvantages:

- Very unattractive.
- More expensive that rip rap.
- Requires manufacturing, storage and transport.
- Blocks will break and move over time.
- Maintenance required from time to time.

3.11.8 Cast concrete blocks

Prefabricated concrete block armour is widely used in places like the Netherlands (Figure 3.41) as cheaper rip rap is not locally available. The interlocking precast concrete blocks are carefully placed against each other on top of a filter layer to form a closed smooth surface. Concrete block stability comes from friction and interlocking. However, significant uplift pressure can occur when high velocity water flows over a block that is not completely flush with surrounding blocks. For more severe conditions and within the wave impact zone, larger blocks should be used. Occasional inspection and maintenance are required to make sure the wall remains in perfect condition (Breteler *et al.*, 2014).

Figure 3.41: Construction of concrete block armour on a Netherlands revetment (Breteler *et al*. 2014)

Advantages:

- Smooth, stable slope that can be walked on.
- More attractive than many other types of seawalls.
- Economics more favourable when mass produced for large projects.

Disadvantages:

- High production costs.
- Time consuming production due to use of moulds and difficulties can occur during the casting process.
- Additional storage and handling costs post manufacture.
- Rocking and settlement can cause breakage and uplifting of the blocks.
- Accurate placement of blocks is difficult in harsh conditions.
- Need larger blocks in more severe conditions.
- Must use a durable concrete mix.

3.11.9 Combination seawalls

Sometimes the best solution for a seawall is a combination of seawall types. Figure 3.42(a) shows concrete tetrapods placed on top of a rip rap wall as an extra protection layer. The tetrapods will help dissipate the force of the waves before they impact the rip rap. Figure 3.42(b) shows a combination of three types of seawalls. A traditional vertical seawall is protected by a revetment made up of rip rap and tetrapods.

Figure 3.42(a): Combination wall of rip rap and tetrapods (Thaler Contracting 2022)
Figure 3.42(b): Concrete seawall with additional protection from rip rap and tetrapod revetment (Coasts 2022)

3.11.10 Groynes

A groyne extends perpendicular out from a beach. It can be a singular structure or part of a groyne field (Figures 3.43(a-b)) and may be constructed out of wood, rocks or concrete. This type of barrier is cheap to construct and requires little maintenance.

Seawalls act as physical barriers to prevent shoreline recession where groynes inhibit the natural movement of sand along the coast. Blocking the natural currents that run parallel to the beach prevents the sand from being washed further along the coast. This maintains the with width of the beach which acts like a natural seawall preventing erosion of the coast. Where sandy beaches have been lost due to coastal erosion, a beach nourishment program may be required where new sand is trucked in to restore the beach. Groynes may be constructed to prevent the new sand being washed further along the coast. However, stopping the natural flow of sand along the coastline may result in increased erosion further down the coast as that beach no longer benefits from natural sand replenishment (Dugan *et* al., 2011).

Figures 3.43(a) and 3.43(b): Groynes trapping sand to prevent erosion (Pikelj 2002, p. 25 and Wikimedia, 2002)

Advantages:

- Low cost and low maintenance.
- Very effective at trapping sand in immediate locality.
- Trapped sand reduces erosion of the coast.

Disadvantages:

- Each groyne protects a relatively small area and erosion still occurs outside this area.
- Multiple groynes are often required.
- Unattractive structures ruin the look of the beach.
- Do not protect coasts from storm driven waves.

3.11.11 Breakwaters

Breakwaters can be constructed perpendicular or parallel to the coast in shallow waters. They are constructed of durable rocks (Figure 3.44(a)) or concrete as their main purpose is to absorb the energy of crashing waves to keep the waters behind the breakwater calm (Southern Dredging, 2022). They are most commonly used to create sheltered harbour areas but can also be used to control beach erosion as part of coastal defence schemes.

Like groynes, breakwaters interrupt natural currents that flow along coastlines. This may stop the natural flow of sand reaching downstream beaches causing erosion further along the coast. This may result in sand being deposited on the sheltered side of the breakwater (Figure 3.44(b)) and increased erosion or scour at the end of the breakwater (DEFRA, 2010).


Figure 3.44(a): Rubble mount breakwater (Southern Dredging 2022)
Figure 3.44(b): Nearshore detached breakwater controlling beach erosion (DEFRA 2010)

Advantages:

- Protects harbours and beaches from storm driven waves.
- Low maintenance.
- Creates areas of calm water that can trap sand in the immediate locality.
- Trapped sand reduces erosion of beaches.

Disadvantages:

- Much more expensive when compared to groynes.
- Only protects a relatively small area and the beach.
- Multiple breakwaters required if used for beach protection.
- Interrupts natural currents and flow of sand along the coast which can cause erosion on beaches further down the coast.
- Unattractive structures ruin the look of the beach.

3.12 Innovative designs

As seawalls become more common, designers, engineers and the community are starting to understand the negative environmental and social impacts seawalls have on the local ecology and resident's livelihood and lifestyle. In some areas, more innovative and creative designs are being built and tested.

3.12.1 Prefabricated multi-terraced thin-walled design.

An alternative to building one massive seawall is a tiered approach using much smaller and lighter prefabricated hollow concrete blocks (Dan *et el.*, 2019). Figure 3.45 shows an example with two thin-walled hollow concrete block tiers on the lower levels and a third solid concrete curved wall on top to reflect waves back during severe storm events. Concrete berm blocks prevent erosion at the toe of each tier making this design much less prone to sliding (due to toe erosion) than traditional walls.

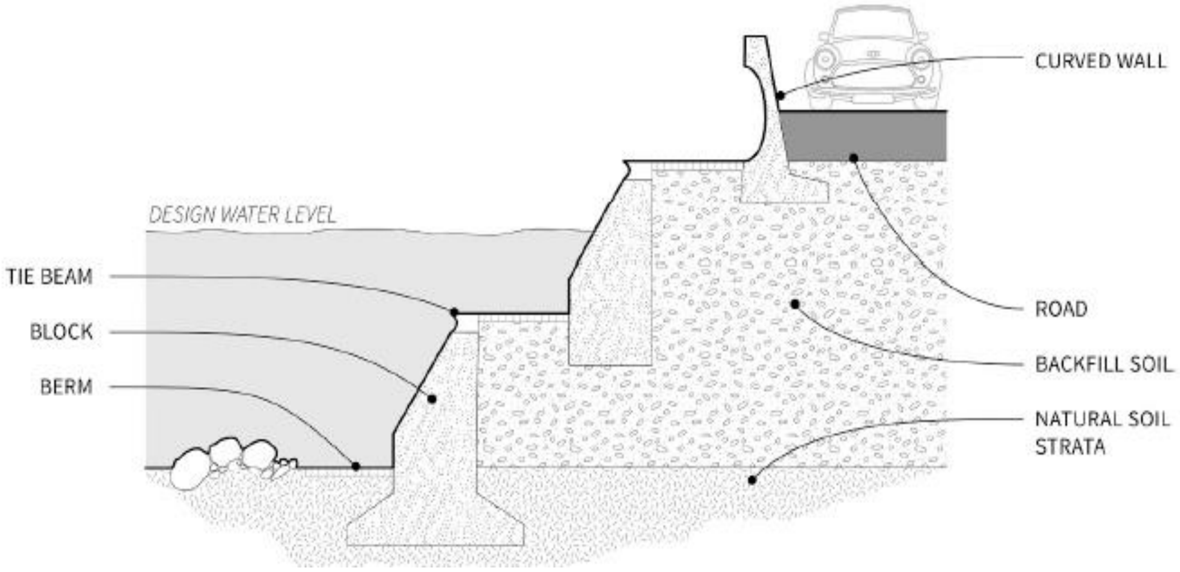


Figure 3.45: Multitiered thin-walled hollow seawall design (Dan *et el*. 2019)

Advantages:

- Prefabricated concrete blocks easy to manufacture and transport to site.
- Lighter design as uses much less concrete than traditional concrete seawalls.
- More cost effective that traditional concrete seawalls.
- Still resists destructive waves.
- More resistant to soil erosion, scouring at the toe and along the beach.
- More stable – displacement over long periods due to continuous wave action is reduced.

Disadvantages

- More complex and more expensive that a rip rap revetment.
- Wider footprint than traditional concrete seawall.

3.12.2 Perforated vertical seawalls

Traditional concrete seawalls have the disadvantage of reflecting the wave back which can cause erosion or scouring at the base of the seawall. This can be overcome by constructing a second vertical wall in front (Figure 3.46). The perforations in the front wall allow some of the wave to pass through the wall and into a chamber between the two walls. A large portion of the wave energy is then dissipated in the chamber rather than being reflected back (Hosseinzadeh *et el*., 2022).

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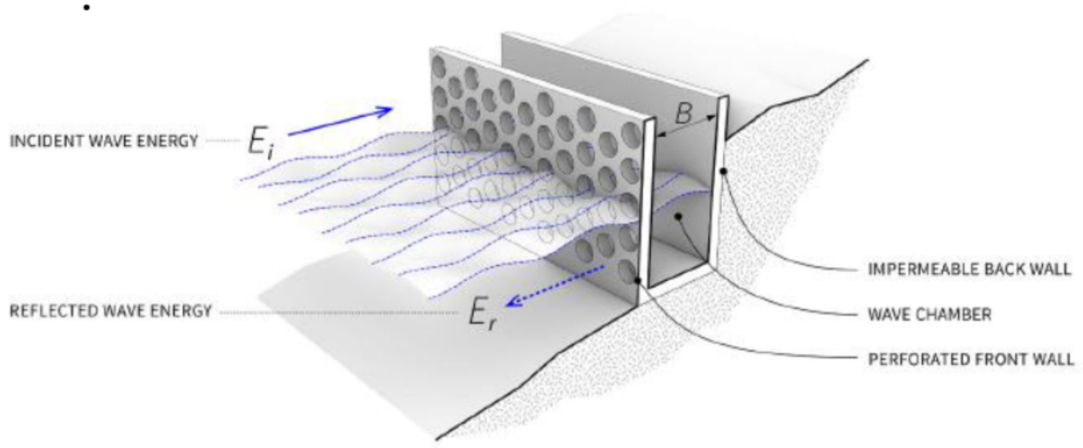


Figure 3.46: Perforated vertical walls dissipate wave energy in the inner chamber and reduce wave reflection (Hosseinzadeh *et el*. 2022).

Advantages:

- Better performance.
- Reduces wave load on the seawall.
- Reduce wave reflection.
- Decreases wave run up and overtopping.
- Reduction in negative effects on coastal ecosystems.
- Improved water quality and marine diversity along the shoreline.

Disadvantages:

- More complex design.
- Increased expense of constructing extra perforated layer to seawall.
- Perforated wall may not be as durable against severe storm waves

3.12.3 Living seawalls and natural shorelines

Traditional seawalls have a poor ecological performance. The natural look of the shoreline is lost and natural habitat destroyed. Rock revetments, and especially the smooth surfaces of concrete seawalls, reduce complexity in the shoreline environment and reduce the level of biodiversity. Living seawalls and natural shorelines address this significant disadvantage.

Living seawalls (Figure 3.47) attempt to reduce the environmental impact of the wall by replacing smooth surfaces with more complex structures bolted onto or Infront of the wall to create many microhabitats. The rough surfaces, textures, holes, crevices, and pools of water mimic the natural environment and provide food and shelter for a wide variety of organisms.

Figure 3.47: Examples of living seawalls, Sydney Harbour (Kars 2022 and Reef Ball Foundation 2020)

Natural or living shorelines ask the question "Is a seawall required at all?" Instead of a seawall, can the placement of rocks, stones, sand and plants be used to strengthen and buffer shorelines (Smith *et al.*, 2020). Natural shorelines gradually slope upwards from a river, estuary or beach. The slope and hard features reduce wave energy and prevent erosion of the shoreline. Areas are incorporated into the slope to grow suitable plants and grasses that cope with occasional inundation and further help prevent erosion (Figure 3.48).

Figure 3.48: Examples of natural or living shorelines (VIMS 2022 and Wavelength 2022)

The three principals (Figure 3.49) for creating a more environmentally sustainable seawall are:

- Maximise the use of native foreshore and estuarine vegetation.
- Maximise habitat diversity and complexity.
- Create low-sloping seawalls or include changes in slope and avoid smooth vertical seawalls.

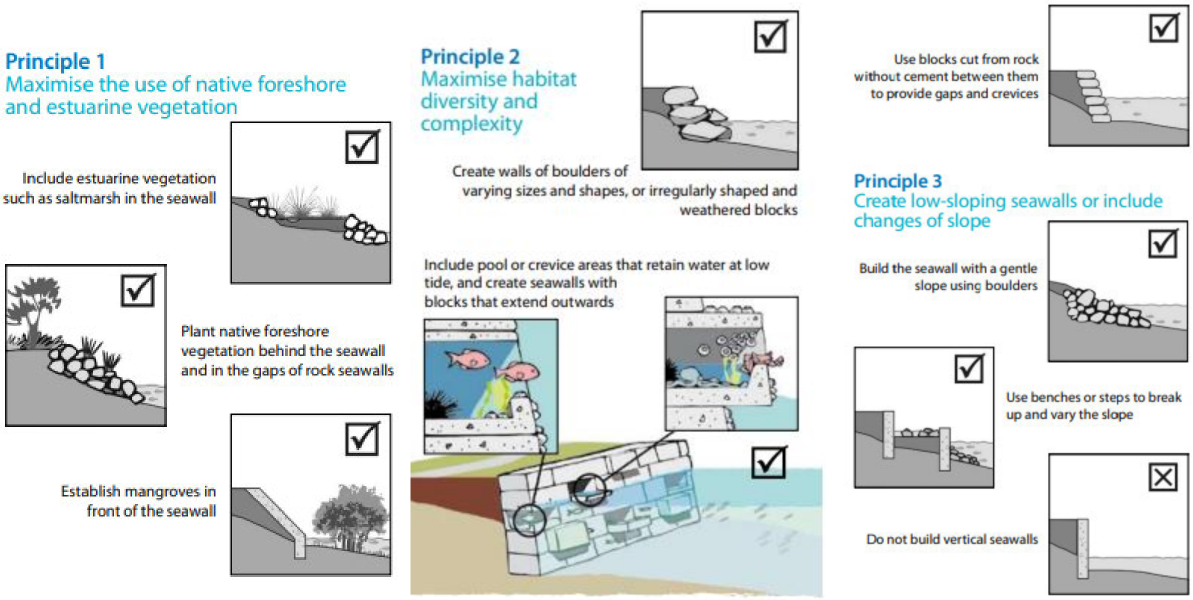


Figure 3.49: Three principals for creating a more environmentally sustainable seawall (Sydney Metropolitan Catchment Management Authority 2009)

Advantages:

- Strengthens and buffers sheltered, low energy coastal environments.
- Reduces erosion.
- Looks more natural – visually pleasing.
- Maximises habitat and biodiversity.
- Supports recreational, commercial and tourism activities.

Disadvantages:

- Extra work and cost to construct.
- Not suitable for high energy environments – only suitable where minimal wave impact.
- Natural shorelines require a lot of space to develop a gradual slope.

3.12.4 Mangroves

Mangroves are salt tolerant evergreen forests found along sheltered, shallow tidal zones along tropical estuaries and coastlines (Figure 3.50). Mangroves are an important wildlife habitat and fish nursery. They improve water quality by trapping sediment and nutrients and preventing them from washing out to off shore coral reefs. Maintaining mangrove ecosystems is crucial to supporting our reef fishery and tourism industries (Blankespoor, Dasgupta and Lang 2017).

In a study by Dasgupta *et al*., (2019) it was found that mangrove roots, trunks and leaves obstruct and reduce the effect of cyclonic storm surges. The velocity of the surge reduced by 29 to 92% and the height 4 to 16.5 cm. However, mangroves should form part of a multi-dimensional protection system and used together with embankments. As well as reducing the area and depth of inundation, mangrove forests also reduce toe erosion and damage to embankments located behind the forest.

A study by Blankespoor, Dasgupta and Lang (2017) also found mangroves to be very effective at preventing coastal erosion and protecting the coastal areas from cyclonic storm surges. However, they noted that sea level rise could pose a significant threat to mangrove forests. There is some historical evidence to suggest mangroves may be able to adapt to gradual sea level rise. However, this may be more difficult where they are blocked from migrating inland. The survival of mangroves is dependent on a multitude of local variables including coastal processes, tidal range, soil salinity, availability of fresh water and sediment. The survival of mangrove forests is therefore uncertain and may require human intervention to maintain the right environmental conditions.

Figure 3.50: Mangroves located at the northern end of Cairns Esplanade (Down Under Tours 2022)

Advantages:

- Very effective at preventing coastal erosion.
- Reduce the impact of cyclonic storm surges on coastlines.
- Important natural habitat and fish nursery.
- Grow naturally around Cairns

Disadvantages:

- Not sufficient protection by itself, still requires an embankment behind the mangrove forest.
- Only suitable where specific natural conditions occur such as in calmer, shallow tidal waters.
- Uncertain future, possibly under threat from sea level rise.

3.13 Summary of learnings

To start the process of developing a specific solution for Cairns, the learnings from researching the experiences of the Netherlands, Japan and other locations around the world have been considered. These lessons demonstrate that it is not as simple as just building a seawall. Consideration also needs to be given to:

- Retreating to higher ground.
- Creating and maintaining natural buffer zones to block the ocean (enhanced natural shorelines and mangroves).
- Reclaiming land (Netherlands)
- Raising land – instead of a thin wall, raise the whole area and build on top of the wall (Japan).
- Landscaping to block wave run up (mounds, raised garden beds, small walls, seating).
- Hardening infrastructure to cope with inundation (ground floor raised, steps up to ground floor).
- Incorporating gates on drains/creeks that close at low tide to stop extreme tides and storm surges flowing up drainage systems to flood the city behind the wall (small version of Thames Barrier).

- Constructing/retaining green zones within the city to soak up excess rain water that builds up behind the wall.
- Consulting local residents and considering their views as well as all economic, social and environmental consequences.

What was learnt about seawalls?

- They work.
- Seawalls can be very expensive.
- They can be ugly.
- They destroy the natural look of the place.
- They destroy the natural ecology, marine life, change currents, cause beach erosion.
- The construction of a seawall can be a very divisive issue within the community it protects with residents having strong and varied opinions.
- Seawalls can negatively impact people's lifestyle and livelihood. This is particularly important in a tourism reliant city like Cairns.
- Even the best seawalls do not last forever. They need occasional maintenance and eventual replacement.
- Seawalls can fail. They need to be properly engineered to prevent scouring in front of the wall and behind the wall when overtopped by wave wash in severe storm events.
- Is a seawall required at all – are there natural solutions?

There is no consensus on what is the best seawall. A large variety of seawalls have been built around the world. The type and scale of the wall being built depends on local factors:

- Budget – often depends on the population base of that area.
- Life span – built for 30 years or 100 years.
- Locality – protecting major infrastructure or more remote locality.
- Space (footprint) available for the wall.
- Materials available (Netherlands have no rocks available so prefer prefabricated concrete).
- Conditions – whether the wall is impacted by waves and if so the severity of wave impact.
- Whether ascetics and the local environment are considered important.
- Subjective opinion of the local authorities and designers/engineers.

3.14 Research conclusion

Chapter 3 addressed the projects first objective by identifying engineering solutions that could protect Cairns from coastal inundation. The chapter provided a detailed review of technologies being implemented around the world to protect coastal cities from being inundated by storm surges and sea level rise. Although the principle means of protection is a seawall, the review identified that construction of a seawall should not be considered in isolation. The impact on residents and the local economy is a crucial consideration. Additionally, hardening infrastructure, raising land and reclaiming land may be incorporated as part of an overall strategy. The review identified that each technology or approach has benefits and limitations. The scale of many of the projects are huge. They put the protection of Cairns into perspective and show that protecting Cairns is both realistic and achievable. However, the suitability of adapting these technologies to the conditions in Cairns has not been explored. An Analytical Hierarchical Process (AHP) will be conducted to identify the most feasible seawall technology for Cairns.

Chapter 4: Development of seawall design for Cairns

4.1 Introduction

There are a large variety of seawall solutions currently in place around the world that successfully provide protection from coastal inundation. This variety of solutions shows there is no consensus as to what is the best type of seawall. Additionally, just because a particular option was chosen or was the best choice in another location does not mean that it is suitable or the best choice for Cairns. This chapter examines issues, such as the local characteristics of Cairns, that need to be considered before conducting an Analytical Hierarchical Process to address objectives one and two.

4.2 Cairns geography

The discovery of gold around Palmer River attracted many settlers to far north Queensland. A humble deep-water port was required and quickly constructed in 1876 in the sheltered Trinity to service the inland goldfields and agricultural lands. The site consisted of low, mosquito infested swamp and sand dunes, surrounded by mangroves and mudflats and only the hardiest pioneers settled. It was only in 1903 that Cairns was declared a town (Cairns Chamber of Commerce 2022).

The modern city of Cairns is located on a narrow coastal strip, squeezed between the ocean and the very steep 200-400 m Great Dividing Range. Immediately north of the central city is the large Baron River flood plain which is suitable for sugar cane fields but not residential development. The popular northern beach suburbs have very limited potential for growth leaving the prime farmland to the south of Cairns as the only significant area for the city to expand (Figure 4.0).

According to the Queensland Governments Comprehensive Coastal Hazard Strategy (Chapter 2.5) the preferred option for managing sea level rise is to retreat from the hazard. However, other than the rural farmland to the south of Cairns, there is nowhere to retreat to. The coastal views, ocean access and facilities that sustain the tourism industry are dependent on the Esplanade precinct continuing to exist. Crucial CBD, industrial and residential infrastructure are all located in the same threatened area. Retreat is not a socially or economically viable solution. The city must be defended by hard engineering solutions.

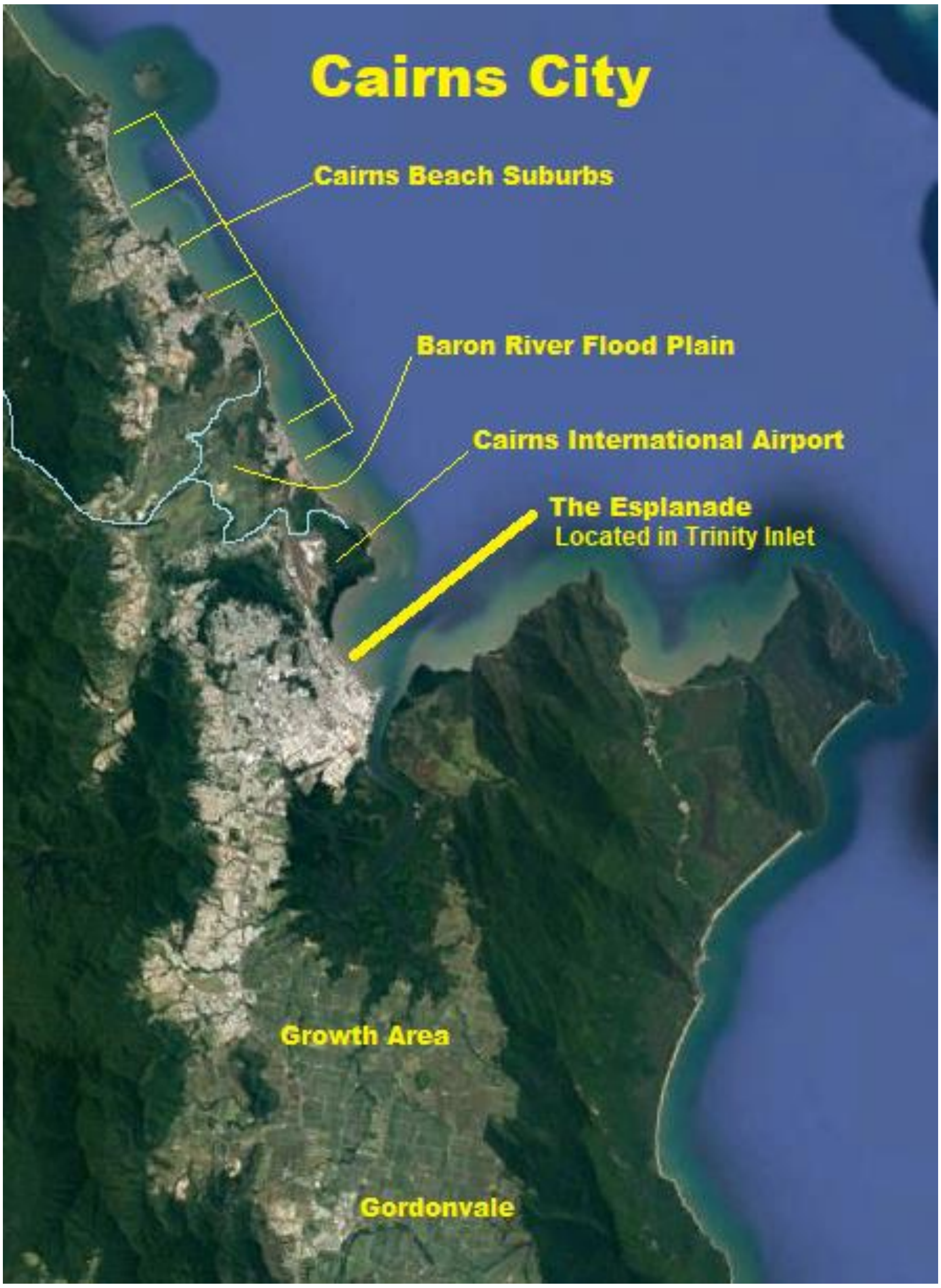


Figure 4.0: Cairns is located on a narrow coastal strip squeezed between the ocean and Great Dividing Range (Source: Google Earth 2022)

4.3 Protection from the Great Barrier Reef

The Great Barrer Reef is situated about 35 km offshore from Cairns. The reef is very effective at absorbing and reducing wave height and energy as they break over the reef. The waves that eventually impact the coastline are therefore much smaller than they otherwise would be and the energy of the wave is more dependent on wind speed rather than wave conditions on the seaward side of the reef (Gallop *et al.* 2014).

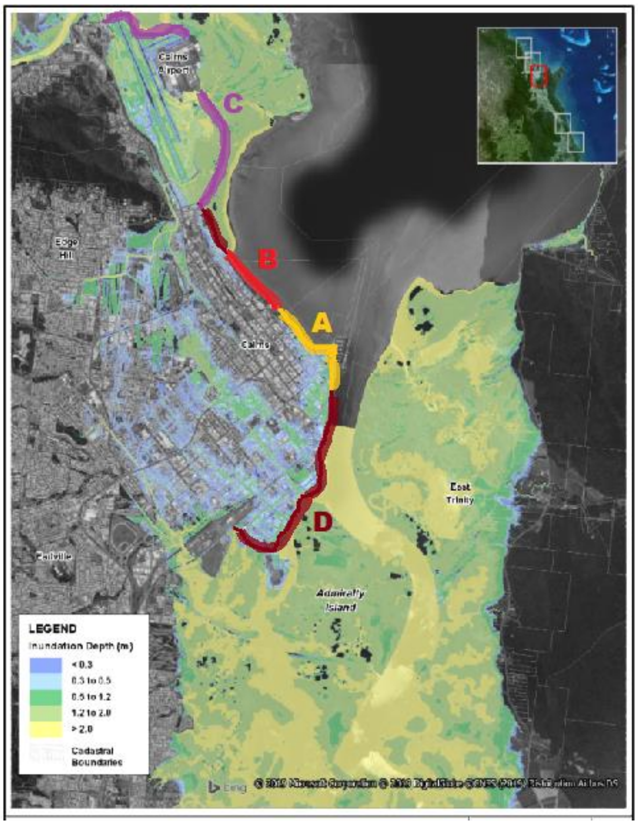
The Great Barrier Reef therefore offers Cairns a degree of natural protection from coastal erosion due to storm and wave impact. This can be seen by the small waves that generally impact the city's northern beach suburbs. The city itself is further sheltered by being located inside the calm waters of Trinity Inlet. As a result, the Cairns Esplanade is not impacted by waves at all. This has allowed mudflats to settle in front of the Esplanade.

This would usually mean a lighter bulkhead structure (Chapter 3.11.1) might be sufficient to protect the Esplanade from erosion. However, Cyclone Yasi, in 2011, shows this is not the case. The small township of Cardwell, located just south of Cairns, is similarly protected by the reef and Hinchinbrook Island (Figures 4.1(a-b)) yet its foreshore was devastated by a cyclonic storm surge and intense wave impact (Chapter 2.3.1). In Cairns, the normally tranquil Trinity Inlet was stirred up by the cyclones winds and became very rough with waves crashing against the Esplanade foreshore (Chapter 2.3.2). Therefore, a more substantial seawall is required in Cairns.

Figures 4.1(a) and 4.1(b): Both Cairns and Cardwell are sheltered by land formations and the Great Barrier Reef but this did not protect Cardwell from being devastated by Cyclone Yasi (2011) (Source: Google Earth 2022)

4.4 Seawall to protect the Cairns Esplanade

As discussed previously, seawall designs vary greatly, and what is best depends on local factors, resource availability and cost constraints. These same issues mean that it may be appropriate to apply different solutions to different sections of the same wall. This is certainly the case in Cairns. Although a total wall length of 13 km will be required, only 3.0 km will need to be built as a strong seawall. The remaining 10 km consists of two simple levee embankments located on each side to prevent water flowing around the seawall. The Cairns Regional Council's sea level rise map is shown below. An increase in sea level of 0.8 m results in much of central Cairns being permanently within the normal intertidal zone. The location of the seawall and earth embankments to protect the city have been superimposed (Figure 4.2).



Esplanade seawall

Section A (southern)	1.8 km
Section B (northern)	1.2 km
Total	3.0 km

Levee embankment

Section C (airport)	4.8 km
Section D (industrial)	5.2 km
Total	10.0 km

Figure 4.2: Cairns city inundation map following a sea level rise of 0.8 m showing the location of the Esplanade seawall (A and B) with levee embankments on each side (C and D) to prevent water flowing around the seawall. (Cairns Regional Council, sea level rise mapping 2022)

Section A (southern Esplanade) and section B (northern Esplanade) contain much of the city's commercial and tourist infrastructure. These crucial areas directly front Trinity Inlet and the ocean. They are exposed to the brunt of king tides and extreme weather so require a strong seawall that can withstand the severest cyclone and storm surge. Sections A and B are the focus of this report.

Section C contains the Cairns International Airport. To the north of the airport is the Baron River and the east is a large mangrove forest. As discussed in Chapter 3.12.4, mangrove forests are very effective at reducing the energy and impact of cyclonic storm surge. However, over the long term it is not known whether mangrove forests will be able to adapt to increasing sea levels. It is likely human intervention will be required to ensure its long-term survival. In the near term, a 4.8 km earth levee embankment behind the mangrove forest will be sufficient to prevent flooding in this area. This is private land belonging to the owners of the airport.

Section D contains a small section on the northern Esplanade behind the mangroves but is mostly deep in the southern facing inlet. This area contains the city's industrial and port areas. As it is sheltered from cyclonic storm surge and wave impact a simple earth levee embankment will be sufficient to protect this area. Over the longer term, blocks of land in the vicinity of the wall should be progressively raised as buildings and infrastructure are replaced.

4.5 Southern Esplanade – current situation (Section A)

A key feature of this section of the Esplanade is the iconic boardwalk that was constructed in 2003. Prior to this, an old concrete retaining wall (Figure 4.3) prevented erosion along the shoreline. The boardwalk was simply built overtop and in front of the old wall (Figures 4.4(a-b)) which continues to prevent erosion to this day.

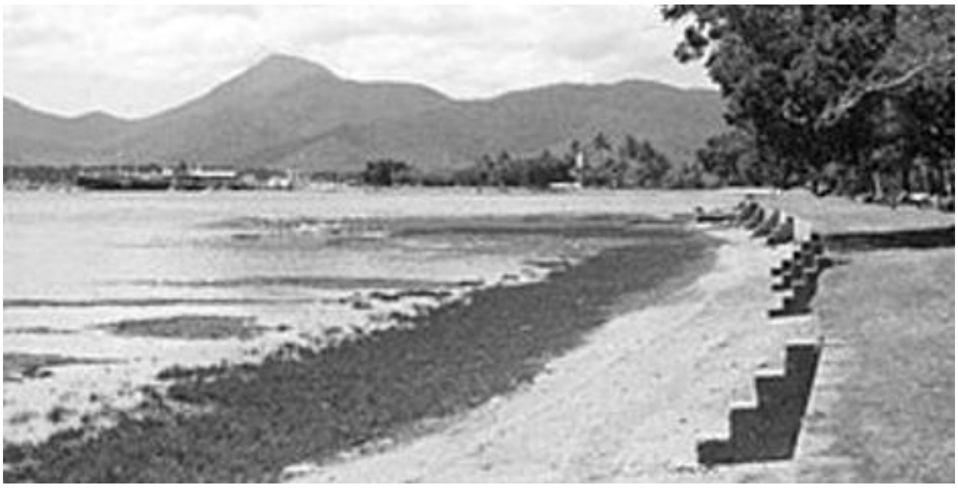


Figure 4.3: Before the construction of the boardwalk a small concrete wall protected the shoreline from erosion (Cairns Museum 2022)

Figure 4.4(a): The new boardwalk was simply built over top of the old concrete wall, this wall is still what protects the southern part of Esplanade from erosion (O'Donoghue 2022)

Figure 4.4(b): The iconic Cairns boardwalk links the esplanade to the ocean and hides the old concrete retaining wall beneath (O'Donoghue 2022)

Tourism infrastructure at the southern end of the boardwalk including the lagoon and Pier complex has been built on reclaimed land. A traditional vertical seawall with a curved topping block to reflect waves back out into the ocean has been built in this section (Figures 4.5).

Figures 4.5: Vertical concrete seawall with a curved block on top protects a section of reclaimed land at the southern end of the Esplanade (O'Donoghue 2022)

Other parts of the wall revert back to rip rap revetments. The more public parts are topped with a decorative concrete edge (Figure 4.6) to blend it in to the parklands while the rip rap revetment in more isolated areas has no decorative edge at the top.

Figure 4.6: Rip rap revetment with a decorative concrete edge fronts some sections of the reclaimed land at the southern end of the Esplanade (O'Donoghue 2022)

However, a small storm surge associated with Cyclone Yasi in 2011 (Figures 4.7(a-b)) show that these walls no longer offer sufficient protection.

Figures 4.7(a) and 4.7(b): Cyclone Yasi (2011) storm surge threatens to inundate Cairns (Cairns Regional Council Storm Tide Evacuation Guide 2021)

4.6 Northern Esplanade – current situation (Section B)

The northern part of the Esplanade was completely undeveloped in the 1950-60s (Figure 4.8) and while there are now attractive parklands and walkways along the entire length, the shoreline itself remains largely in its natural state today (Figure 4.9) with a small sandy beach and mudflats at low tide. King tides have started to erode a few sections (Figure 4.10(a)) and these areas have been protected by a small wall of large boulders (Figure 4.10(b)). However, this type of wall is not a permanent solution and only slows down the rate of erosion. King tides have entered the gaps between the boulders and large cavities are forming behind the boulders.

Figure 4.8: The undeveloped northern Esplanade in the 1950-60's (Cairns Museum 2022)

Figure 4.9: Northern Esplanade shoreline remains mostly in its natural state today (Aussie Towns 2022)

Figure 4.10(a): North Esplanade shoreline suffers erosion during king tide events (Cairns Regional Council 2022)
Figure 4.10(b): Large boulders offer some protection from erosion (O'Donoghue 2022)

4.7 Seawall design analysis

To determine which seawall solution is most suitable for these local Cairns conditions, alternatives solutions are compared and evaluated against specific criteria. This process starts with a preliminary evaluation to exclude the options which are clearly not suitable for Cairns. The remaining options will all be suitable alternatives. An in-depth analytical hierarchy process (AHP) will then be applied to the remaining alternatives to determine the most suitable option for Cairns.

4.8 Preliminary evaluation

If there is no possibility of a solution being implemented in Cairns there is little point in conducting a more thorough design evaluation through an AHP. To evaluate if a solution is suitable for Cairns, three critical factors have been determined. The options that do not meet these criteria are excluded as possible solutions (Table 2).

The first criterion is that the seawall must have a design life 50 years. Over the next 50 years ocean height is predicted to increase by up to 0.8m. With a safety barrier of 0.2m, the minimum height of the wall is to be 1m above the current level of the Esplanade land surface. However, this does not allow for additional sea height during cyclonic storm surge events. Therefore, the ideal wall height will be 1.2 m above current levels.

Cairns has a population of 168,449. As a small to medium sized city and it would be difficult to justify the scale and expense of some of the flood protection measures that have been constructed overseas. Options that may be suitable for a European city of 2 million people may not be realistic in Cairns. Therefore, cost is an important factor in determining if any solution is suitable for Cairns.

Cairns is a world-renowned international tourist destination that relies on revenue from tourists for employment and funds to sustain the city. The tropical environment, visual appeal of the Esplanade and direct access to the ocean and great barrier reef are crucial elements that attract tourists to Cairns. Any solution must not negatively impact the social and environmental aspects that support this industry. The final solution or combination of solutions must contribute to maintaining the cities status as a premier tourist destination.

Table 2: Preliminary analysis to exclude options that are not clearly not suitable for Cairns

Designs	Cairns Suitability Evaluation Categories		
	Meet minimum sea level increase for 50 years 1.2m above current level	Affordable for a city the size of Cairns	Fit in with Cairns status as a premier tourist destination
Bulkheads	✗	✓	✗
Gabions	✓	✓	✗
Wood, plastic and metal seawalls	✗	✓	✓
Simple vertical seawalls	✓	✓	✓
Curved seawalls	✓	✓	✓
Stepped seawalls	✓	✓	✓
Concrete revetments	✓	✓	✓
Rip rap revetment	✓	✓	✓
Tetrapods	✓	✓	✗
Cast concrete block armour	✓	✗	✓
Groynes	✓	✓	✗
Breakwaters	✓	✓	✗
Perforated vertical seawall	✓	✗	✓
Terraced seawall	✓	✗	✓
Natural shore line	✓	✓	✓

4.8.1 Excluded options

Bulkheads are most suitable for protected calm water situations. Whilst Cairns is located in sheltered Trinity inlet, the waters are not calm during cyclonic storm surges and water conditions may change as sea levels rise. The industrial look of a bulkhead does not fit with the look required for a premier tourist destination and it will not have the longevity required. The same issues have excluded gabions, wood, plastic and metal seawalls.

Tetrapods, groynes and breakwaters are great options for certain situations but do not fit with maintaining the natural look of Trinity Inlet. They would negatively impact the aesthetics of the Esplanade and the tourism industry would suffer.

Concrete block armour on a revetement is a great alternative where rock armour is not available. However, it is expensive and rocks are readily available in Cairns should a revetement option be chosen.

Perforated vertical seawalls and terraced seawalls are innovative ideas in development. They have yet to be proven and are more expensive that regular seawalls.

These seawalls have been excluded from further evaluation as they are considered unsuitable or there are clearly better options available in the Cairns location.

4.8.2 Remaining options

The remaining seawall options meet the preliminary evaluation criteria and have therefore been determined as suitable to be constructed along the Cairns Esplanade foreshore:

- Simple vertical seawall
- Curved seawall
- Stepped seawall
- Concrete revetment
- Riprap revetment
- Natural shoreline

In the next chapter, an Analytical Hierarchical Process will be used to evaluate these alternatives in more detail in order to identify the most suitable to construct along the Cairns Esplanade.

Chapter 5: Permanent seawall - Analytical Hierarchical Process

This chapter addresses objective 2 by evaluating seawall alternatives through an analytical hierarchical process to identify the best seawall solution to construct along the Cairns Esplanade. The chapter begins by explaining what the process is and the various criterial that will be evaluated. Subjective weightings are then allocated to each criterion depending on their relative importance and the criteria evaluated two at a time. The results are analysed through a series of comparison tables to identify the most suitable alternative.

5.1 Analytical Hierarchy Process (AHP)

Many decisions are complex because they involve the interaction of many different factors that make the best choice unclear. The decision process may be further complicated by some factors being of minor importance whilst others are crucial. Therefore, not only is it essential to identify all the factors that need to be considered but also which ones are the most important and the degree of that importance. Yet another issue is that whilst many factors, such as cost and size, are tangible and easily measured, others such as aesthetics or the importance of the environment are intangible and not easily measured. The importance of these factors is very subjective and more to do with human perception, experience and opinion (Saaty 2012).

Professor Thomas Saaty of the University of Pittsburgh developed a way of making these complex decisions that takes into account all of these complexities through an **Analytical Hierarchy Process (AHP).** This involves making decisions on the relative importance of all the individual factors which are then compared and evaluated in a logical and transparent process that provides justification for the final decision.

The AHP process compares the alternative seawall options against multiple criteria (factors) that have been weighted according to perceived importance. Allocating numerical scores allows for direct comparison and the identification of the best option out of the alternative seawalls. The three steps of the AHP are:

1. Develop a hierarchy for the criteria (Figure 5.0).
    - Top level is the overall objective – the most suitable seawall.
    - Middle level/s are the criteria that will be considered in the AHP.
    - Bottom level is the alternative types of seawalls under consideration.
2. Make judgements about the relative importance of each criterion by comparing two criteria at a time and allocate a weighting ratio.

3. Score the alternative types of seawalls relative performance against each criterion in the hierarchy (complex maths calculations and comparison tables).

The alternative seawall with the highest numerical value is the best choice.

The criteria that will determine the most suitable seawall are:

- Sea water, storm and wave resistance
- Design life and durability
- Aesthetics
- Future upgradability
- Material availability
- Ease of construction
- Footprint
- Environmental integration and sustainability

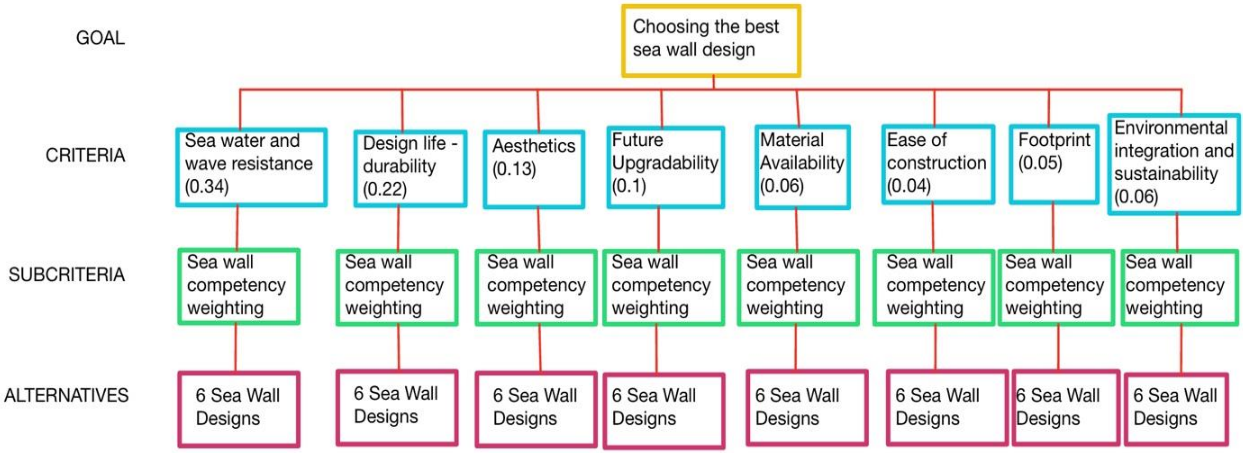


Figure 5.0: Hierarchy diagram illustrates the AHP process

5.2 Criteria descriptions

The overall objective of the AHP is to identify the best seawall to prevent inundation and erosion along the Cairns Esplanade and in doing so protect the city's infrastructure and economic prosperity. This section describes each of the criteria that will contribute to achieving this goal and then discusses why each is important and how this importance applies to Cairns. Questions are then identified that assist in establishing how well a design might meet the criteria.

5.2.1 Sea water, storm and wave resistance

An effective seawall for Cairns must be well constructed and built out of tough materials that can withstand the harsh tropical sun, humidity, salt water, violent storms, torrential rain and the impact forces from cyclone induced waves. Loose rock revetments absorb wave energy in their cracks and crevices where solid concrete vertical walls reflect most of the wave energy back which can cause erosion in front of the wall and further along the beach over time. However, as Cairns is located in a sheltered inlet that is not usually subject to wave action, this aspect is not significant. A key consideration is that Cairns is impacted by the occasional tropical cyclone and associated storm surge which may batter and perhaps overtop the wall. The severity and number of tropical cyclones is expected to increase with global warming and sea level rise will result in the sea being permanently against the wall, rather than just at high tide, in future decades. The seawall must therefore be very robust and designed so that it will not be damaged or fail during extreme weather events. Aspects of the seawall design that need to be considered are:

- Does the wall degrade if constantly exposed or submerged by salt water?
- Can the wall stand up to tropical weather and severe storms?
- Can the wall stand up to being overtopped by a cyclonic storm surge?

5.2.2 Design life – durability

From the day they are built, seawalls are constantly being degraded and eroded by the ocean environment, salt water and wave impact. Therefore, no matter how durable the wall, they all have a limited life span. For many walls this may be 25 to 50 years. The best walls may have a design life of 100 years (Coastal Engineering Solutions 2022). As well as being very expensive, construction of a seawall along the Esplanade will be very disruptive to people and business. It is therefore important that the wall has a reasonable design life before needing to be replaced and requires minimal maintenance once constructed.

Aspects of seawall design that needs to be considered are:

- What is the expected life span of seawall design?
- Does the life span provided justify the cost of construction?
- What maintenance is required and how often will repairs be needed?

5.2.3 Aesthetics

The aesthetic look and feel of a city are one of the most important elements of its identity. They distinguish it from other cities and change a person's feelings, senses and emotions about the city (Al-Hinkawi,W & Ramdan, A 2016). The aesthetics can be related to the build environment and also the natural environment. For example, a city like Paris is filled with history, culture, traditional architecture and has a European feel while New York is a huge city where people are dwarfed by giant skyscrapers and the compact streets are alive with the hustle and bustle of American city life. Tourists flock to Cairns because it is very different to where they live. Cairns has a relaxing tropical atmosphere and is known for adventure and its outdoor lifestyle. The city has an abundance of natural attractions such as the reef and rainforest at its doorstep. A key part of the tourist experience is the spectacular setting of the Esplanade and the social aspects that are provided by its many cafes, restaurants and bars. The foreshore parklands connect the Esplanade to the ocean. The parklands are a hive of activity with crowds of people taking advantage of the shady trees, gardens, large lawns, walkways, Muddy's playground, volleyball courts, skateboard park, pool and BBQs to exercise and socialise. The city's connection and views of the ocean, mangroves and mudflats are key aspects that make Cairns a special place and a premium international tourist destination. The cities economic prosperity relies on its aesthetic look and feel. This must be considered when choosing the best seawall solution.

- Does the seawall solution blend into the foreshore environment, is it visually pleasing or an eyesore?
- Will the solution negatively impact the reputation of Cairns as a fun loving, outdoor nature based premium tourist destination?
- Will the seawall degrade the tourist experience, reduce connection with the ocean, block views?

5.2.4 Future upgradability

Future upgradability is an important aspect of choosing the right design. The rate of global warming is uncertain and so is the rate of sea level rise. The ease with which the seawall can be upgraded if sea levels rise faster than expected is an advantage. Considerable time, money and resources would be saved the foundations and base of the wall could be retained and additional height added without replacing the whole wall. Additionally, sea level is expected to continue rising well into the next century. Therefore, when the seawall is eventually replaced the replacement will need to be build higher again.

- Can the wall be upgraded and made higher if sea levels rise faster than expected?
- How easy and expensive would this be?
- How easy will it be to replace the wall at the end of its life?

5.2.5 Material availability

Seawalls around the world are built out of a wide range of materials. Often the choice of materials comes down to what is available in the local area. For example, the Netherlands prefers usually more expensive cast concrete block armour walls because they do not have a supply of rip rap rocks locally. Once the cost of purchasing rip rap from another country, long distance transport and storage are included, the usually cheaper rip rap wall may become more expensive than one made with cast concrete block armour. The availability of material locally is therefore an important aspect in keeping the cost of the wall lower. Evaluation of different materials that can be used to construct each type of retaining wall will be evaluated by following questions:

- Are needed construction materials available in Cairns?
- Do materials need to be shipped?
- Can manufacturing be done locally?

5.2.6 Ease of construction

Ease of construction refers to the practicalities of building and integrating the new wall design into the current foreshore. Does it tie in with current infrastructure, how easy is it to build the wall in the Esplanade location, is the design able to be built on mud flats. This is important as the easier the wall is to construct, the quicker the construction process, less disruption will be caused and the lower construction costs are likely to be:

- Can the wall be easily constructed on the Esplanade location and does it fit in with current features and infrastructure along the foreshore?

5.2.7 Footprint

Footprint refers to the width of land needed for different design options. A vertical wall and its footings may only be 1 m wide whilst a rip rap revetment may be 10 m and a natural shoreline 20 m. The importance of this criteria depends on how much space is available. Where space is limited, a narrow wall may be preferred.

- How wide is the footprint required for the wall?
- How much space is available for the footprint, that is, is there limited space?

- If there is plenty of space, can the space taken up by a wide footprint alternative be better used, for example, as parkland?

5.2.8 Environmental integration and sustainability

The success of Cairns as a tourist destination is built on its natural attractions – reef, rainforests, native animals, birds, fishing and tropical environment. Environmental integration refers to the degree that the seawall design enhances or takes away from the natural surroundings. Environmental sustainability refers to whether the design has any negative effects on the natural environment (mudflats, mangroves, wildlife) during construction or during its lifetime. Is the wall made out of natural materials such as rocks that create or at least maintains natural habitat? Additionally, is the wall made of environmentally friendly, non-toxic materials? If the wall was destroyed would material washed into the natural ecosystem be harmful to the environment or wildlife? Questions when evaluating seawall design in relation to environmental integration and sustainability include:

- Does the look of the wall fit in with the natural environment?
- Is the wall constructed out of ecofriendly, natural materials or could the materials become toxic to sea life?
- Does the wall have any negative impacts on natural ecosystems?
- Does the wall create natural habitat and enhance the natural environment?

5.3 Criteria importance justification

This section starts the process of allocating a numerical score to each criterion. Two criteria are compared at a time to identify the relative importance of each criterion. For example, as shown in Table 3, sea water and wave resistance are considered to be as equally important as design life and durability. However, Seawater and wave resistance is considered 5 times more important than aesthetics. The allocated weighting is based on subjective judgements. The justification for the importance rating is explained in the 'Importance Justification' column.

Table 3: Comparison of criteria pairs and allocation of an importance multiplication factor

Criteria 1	Importance Multiplication	Criteria 2	Importance Justification
Sea water and wave resistance	=	Design life – durability	**<u>Sea Water Resistance = Durability:</u>** Sea water resistance refers to how it stands against the natural degradation caused by wave forces and salt water. While durability refers to how long wall will last and if the cost justifies the design life. Both are key as if the design fails to meet these criteria it fails at being a seawall. Hence importance was determined to be equal.
Sea water and wave resistance	*5	Aesthetics	**<u>Sea Water Resistance 5x more important than Aesthetics:</u>** Although aesthetics is a very important factor for Cairns, its importance is still considerably less the sea water resistance which consists of the basic parameters for a seawall to function correctly. As an aesthetically designed seawall is not much of a seawall if it can't resist the oceans forces.
Sea water and wave resistance	*7	Future Upgradability	**<u>Sea Water Resistance 5x more important than Future Upgradability:</u>** Future upgradability refers to the ease at which the wall can be increased in height at a future date. However, these upgrades will not matter if the prior seawall fails to protect against ocean forces.
Sea water and wave resistance	*7	Material Availability	**<u>Sea Water Resistance 7x more important than Material Availability:</u>** Material availability is expected to be a minimal issue for most design options; hence it is considerably more important how the designs resists sea water and waves.
Sea water and wave resistance	*7	Ease of construction	**<u>Sea Water Resistance 7x more important than Ease of Construction:</u>** If the design fails to protect from sea water and waves it matters little how complex or easy the construction process is.
Sea water and wave resistance	*5	Footprint	**<u>Sea Water Resistance 5x more important than Footprint:</u>** There is already a considerable footprint available for construction in Cairns even though it is a very important aspect it is still significantly less important than the seawall functioning correctly by resisting waves.
Sea water and wave resistance	*5	Environmental integration and sustainability	**<u>Sea Water Resistance 5x more important than Environmental integration:</u>** Creating a safe environment to encourage ecological growth is key for a more environmentally friendly future, however the design needs to be resistant to sea water and waves so it can last into the future.

			Hence was environmental integration and sustainability was decided to be less important.
Design life – durability	=	Aesthetics	**Durability = Aesthetics:** For a design to be durable and long lasting in Cairns it also needs to Aesthetically fit into surrounding environment, otherwise it will degrade the tourist aesthetics. Therefore, minimal point in having a design that last a long time if it's not also aesthetically pleasing, hence why importance was decided to be equal.
Design life – durability	*5	Future Upgradability	**Durability 5x more important than Future Upgradability:** If the design has lack of durability, it will not be in a suitable state to benefit from future upgrades, therefore durability is a key feature for future upgradability to occur.
Design life – durability	*3	Material Availability	**Durability 3x more important than Material Availability:** The durability of a seawall is based on the materials that constructs it. Having greater durability is more important than the effort required to obtain the available material.
Design life – durability	*5	Ease of construction	**Durability 5x more important than Ease of Construction:** The complexity of design is less important than its durability as the increase in life expectancy for a seawall will out way the complexity of designing it.
Design life – durability	*5	Footprint	**Durability 5x more important than Footprint:** As there is a large footprint available for construction of seawall in cairns, ensuring that the durability of the seawall is adequate is more important than having a few more metres for greenery.
Design life – durability	*3	Environmental integration and sustainability	**Durability 3x more important than Environmental integration and sustainability:** Considering environmental integration and sustainability is important however it is less so than making sure the durability can provide many decades of use. As it will be in vain to have a highly environmental wall that has a short life span due to lack of durability.
Aesthetics	=	Future Upgradability	**Aesthetics = Future Upgradability:** As future upgradability is based on the existing design and to further improve on top of it. It would be expected that the Aesthetics will need to be up to standard with any future upgrades. Hence why equal importance was given.
Aesthetics	*3	Material Availability	**Aesthetic 3x more important than Material Availability:** Materials being used aren't as useful if they degrade the tropical aesthetic required for cairns foreshore. Hence was decided to be of less importance.
Aesthetics	*5	Ease of construction	**Aesthetic 5x more important than Ease of construction:**

			Adding complexity of construction to make the seawall fit into the tropical aesthetic of cairns is a worthy sacrifice as Cairns in a tourist city. Relying on it for a large portion of the cities income hence was decided to be of greater importance.
Aesthetics	*3	Footprint	**<u>Aesthetic 5x more important than Footprint:</u>** Using a wider footprint to provide a nice experience for tourist on the foreshore is a compromise that would easily be made. As it's a key aspect having a tourist friendly foreshore.
Aesthetics	=	Environmental integration and sustainability	**<u>Aesthetic 5x more important than Environmental integration and sustainability:</u>** A key aspect of tourism in cairns in the tropical environment, sea views and access to the reef. Having an aesthetics that encourages this is just as key that environmental integration that will illustrate it.
Future Upgradability	*2	Material Availability	**<u>Future Upgradability = material availability:</u>** Having future upgradability is a key feature in designing a seawall for the future hence is more important them material availability however it is still key to be able to have access to materials for future construction.
Future Upgradability	*3	Ease of construction	**<u>Future Upgradability 3x more important than Ease of construction:</u>** Even if construction becomes more complex it is key to have capabilities as for future upgrades as if the seawall needs to be deconstructed it will increase construction costs for future upgrades.
Future Upgradability	*5	Footprint	**<u>Future Upgradability 5x more important than footprint:</u>** Large footprint is available therefore it will be beneficial to sacrifice by increasing footprint to give seawall capability to protect cairns from sea level rise in future.
Future Upgradability	=	Environmental integration and sustainability	**<u>Future Upgradability = Environmental integration and sustainability:</u>** Protecting Cairns through future upgradability and protecting the surrounding environment that is a key feature of Cairns. Both equally important as Cairns wouldn't be as popular of tourist destination of it didn't have it's surrounding environment.
Material Availability	=	Ease of construction	**<u>Material Availability = Ease of construction:</u>** Both criteria will lead to a cheaper quicker construction time therefore equally beneficial to the design.
Material Availability	=	Footprint	**<u>Material Availability = Footprint:</u>** Material availability and footprint size are both key considerations when designing a seawall with both being equally important when evaluating options.
Material Availability	*2	Environmental integration and sustainability	**<u>Material Availability 2x more important than Environmental integration and sustainability:</u>** Being able to obtain materials that are environmentally friendly is the key step in creating

			integration and sustainability therefore without access to the materials the environmental aspect cannot occur therefore it was decided to make it twice as important.
Ease of construction	=	Footprint	**Ease of Construction = Footprint:** Both criteria relate to the ability to construct the design and are equally important to consider as a balance needs to be found.
Ease of construction	=	Environmental integration and sustainability	**Ease of Construction = Environmental integration and sustainability:** Ease of construction compared to environmental integration and sustainability illustrate two key options, considerations when designing a seawall with both being equally important when evaluating options.
Footprint	=	Environmental integration and sustainability	**Footprint = Environmental integration and sustainability:** Footprint and environmental integration and sustainability are both key considerations when designing a seawall with both being equally important when evaluating options.

5.4 Weighting factor calculations

The previous section determined the relative importance of each criterion on a pair-wise basis. The importance of each criterion is converted to numerical values (Table 4). For example, if a criterion is 5 times more important that the other it has a score of 5. The inverse of this is that if a criterion is 5 times less important it has a score of 0.20 (out of 1). The value of each pair comparison is then incorporated into a pair-wise comparison matrix (Tables 5 and 6).

Table 4: Scale of weight the importance of each pair-wise comparison (inverse ratings)

Importance Scale for Pair-wise comparison matrix		
Equally important	1	1
	2	0.5
Moderate differentiation in importance	3	0.333
	4	0.250
Large differentiation in importance	5	0.200
	6	0.167
Very Large differentiation in importance	7	0.143
	8	0.125
Extreme differentiation in importance	9	0.111

Table 5 summarises the score for each pairwise comparison. The total sum of importance of each criterion is calculated by adding up each column.

Table 5: Pair-wise comparison matrix

Pair-wise comparison matrix								
	Sea water and wave resistance	Design life – durability	Aesthetics	Future Upgradability	Material Availability	Ease of construction	Footprint	Environmental integration and sustainability
Sea water and wave resistance	1.00	1.00	5.00	7.00	7.00	7.00	5.00	5.00
Design life – durability	1.00	1.00	1.00	5.00	3.00	5.00	5.00	3.00
Aesthetics	0.20	1.00	1.00	1.00	3.00	4.00	3.00	1.00
Future Upgradability	0.14	0.20	1.00	1.00	2.00	3.00	5.00	1.00
Material Availability	0.14	0.33	0.33	0.50	1.00	1.00	1.00	2.00
Ease of construction	0.14	0.20	0.25	0.33	1.00	1.00	1.00	1.00
Footprint	0.20	0.20	0.33	0.20	1.00	1.00	1.00	1.00
Environmental integration and sustainability	0.20	0.33	1.00	1.00	0.50	1.00	1.00	1.00
Sum:	3.03	4.27	9.92	16.03	18.50	23.00	22.00	15.00

The next step in the calculation process is divide the sum total in Table V by each of the individual scores shown in Table V. For example, 'Footprint' versus 'Sea water and wave resistance' has a score of 0.2 with the column sum being 3.30. The calculation is therefore 0.2 divide by 3.03 = 0.066 (rounded to 0.07). The 0.07 score is then transferred to the Normalised Pair-wise comparison matrix (Table W).

Once all scores have been transferred, the average in each row in Table W is calculated to find the weighting (out of 1) for each criterion. For example, the average value for the 'Ease of construction' row is 0.04, therefore the weighting for 'Ease of construction is 0.04. The sum of all the weightings adds up to 1.00.

Table 6: Normalised pair-wise comparison matrix (final weighting for each criterion out of 1.00)

Normalised Pair-wise comparison matrix									
	Sea water and wave resistance	Design life – durability	Aesthetics	Future Upgradability	Material Availability	Ease of construction	Footprint	Environmental integration and sustainability	Criteria Weights
Sea water and wave resistance	0.33	0.23	0.50	0.44	0.38	0.30	0.23	0.33	0.34
Design life – durability	0.33	0.23	0.10	0.31	0.16	0.22	0.23	0.20	0.22
Aesthetics	0.07	0.23	0.10	0.06	0.16	0.17	0.14	0.07	0.13
Future Upgradability	0.05	0.05	0.10	0.06	0.11	0.13	0.23	0.07	0.10
Material Availability	0.05	0.08	0.03	0.03	0.05	0.04	0.05	0.13	0.06
Ease of construction	0.05	0.05	0.03	0.02	0.05	0.04	0.05	0.07	0.04
Footprint	0.07	0.05	0.03	0.01	0.05	0.04	0.05	0.07	0.05
Environmental integration and sustainability	0.07	0.08	0.10	0.06	0.03	0.04	0.05	0.07	0.06
								Sum:	1.00

With a score of 0.34 seawater and wave resistance is considered to be the most important selection criteria, whilst ease of construction is the least important.

5.5 Criteria rating factors

Table 7 summarises the results of the pair-wise comparison matrix and ranks the criteria in order of importance. The table also contains questions that will be used to evaluate each alternative seawall against the criteria. This provides transparency in the selection process.

Table 7: Criteria weighting factor and evaluation point summary

Criteria	Weighting Factor	Ranking	Seawall Evaluation Points
Sea water and wave resistance	0.34	1	• Does the wall material degrade if constantly exposed or submerged by salt water? • Can the wall stand up to tropical weather and severe storms? • Can the wall stand up to being overtopped by a cyclonic storm surge?
Design life – durability	0.22	2	• What is the expected life span of seawall design? • Does the life span provided justify the cost of construction? • What maintenance is required and how often will repairs be needed?
Aesthetics	0.13	3	• Does the seawall solution blend into the foreshore environment, is it visually pleasing or an eyesore? • Will the solution negatively impact the reputation of Cairns as a fun loving, outdoor nature based premium tourist destination? • Will the seawall degrade the tourist experience, reduce the connection with the ocean or block views?
Future Upgradability	0.10	4	• Can the wall be upgraded and made higher if sea levels rise faster than expected? • How easy and expensive would this be? • How easy will it be to replace the wall at the end of its life.
Material Availability	0.06	5	• Are needed construction materials available in Cairns? • Do materials need to be shipped? • Can manufacturing be done locally?
Environmental integration and sustainability	0.06	6	• Does the look of the wall fit in with the natural environment? • Is the wall constructed out of ecofriendly, natural materials or could the materials become toxic to sea life? • Does the wall have any negative impacts on natural ecosystems? • Does the wall create natural habitat and enhance the natural environment?
Footprint	0.05	7	• How wide is the footprint required for the wall?

			• How much space is available for the footprint, that is, is there limited space? • If there is plenty of space, can the space taken up by a wide footprint alternative be better used, for example, as parkland?
Ease of construction	0.04	8	• Can the wall be easily constructed on the Esplanade location and does it fit in with current features and infrastructure along the foreshore?
Total Weight Factor	1	-	

5.6 Design option weighting justification and comparison

Tables 8(a) to (f) introduce each of the alternate seawall designs into the calculation process. Each alternate seawall has its own table. The seawall is assessed against each selection criteria and allocated a subjective score out of 100. The reasons for this judgement given in the 'Justification' column.

Table 8(a): Design criteria evaluation vertical seawall

Design: Vertical Seawall		
Criteria	**Weighting out of 100**	**Justification**
Sea water and wave resistance	75	• Seawall is made of concrete and is resistant to salt water. • Though wall is strong it lacks features that will deflect the energy from waves leading to faster degradation.
Design life – durability	75	• AS4997 2005 standard design life 50 years. • Wall is more standard option therefore cheaper option when it comes to engineered concrete walls. • Minimal maintenance needed due to concrete strength.
Aesthetics	50	• Can be a large unattractive structure when compared to natural shorelines • Able to be built on by docks hiding vertical seawall below.
Future Upgradability	100	• As the ability to be built on top of or behind and still be functional.
Material Availability	95	• Concrete required for construction commonly available
Ease of construction	90	• Easy to construct and design
Footprint	100	• Narrow providing a small footprint
Environmental integration and sustainability	40	• Can score and erode stand due to waves. Destroys the natural shoreline, poor ecological properties.

Table 8(b): Design criteria evaluation curved seawall

Design: Curved Seawall		
Criteria	**Weighting out of 100**	**Justification**
Sea water and wave resistance	100	• Seawall is made of concrete and is resistant to salt water. • Highest level of protection against severe wave impact due to curve diverting energy of waves.
Design life – durability	90	• AS4997 2005 standard design life 50 years. • Wall is more engineered option therefore will be more costly option. • Minimal maintenance needed due to concrete strength. • Durability helped by ability to redirect wave energy. • If failure occurs, it can succumb to rapid and complete failure.
Aesthetics	50	• Can be a large unattractive structure when compared to natural shorelines • Able to be built on by docks hiding vertical seawall below.
Future Upgradability	30	• Hard to upgrade and build upon as needs to be at high enough level that wave peaks cash against it, (useless under water).
Material Availability	95	• Concrete required for construction commonly available
Ease of construction	60	• Requires large amount of engineering to design and construct. • Can be intergraded in range of sizes and can be built upon other designs such as vertical seawalls.
Footprint	85	• Has a larger footprint then vertical seawall however smaller the other options such as stepped or revetments
Environmental integration and sustainability	60	• Causes less scouring in comparison to other options, causes less disturbance. • No area for ocean creatures to make home.

Table 8(c): Design criteria evaluation stepped seawall

Design: Stepped Seawall		
Criteria	**Weighting out of 100**	**Justification**
Sea water and wave resistance	90	• Seawall is made of concrete and is resistant to salt water. • Stepped designs break up waves reducing the impact force.
Design life – durability	75	• AS4997 2005 standard design life 50 years. • Wall is more engineered option therefore will be more costly option. • Minimal maintenance needed due to concrete strength.
Aesthetics	60	• Can be a large unattractive structure when compared to natural shorelines • Steps can be tied into designs as a feature to access shore front making it blend in better.

Future Upgradability	90	• Can act as a base layer for a vertical or curved seawall to be built on top.
Material Availability	95	• Concrete required for construction commonly available
Ease of construction	60	• Requires large amount of engineering to design and construct.
Footprint	80	• Requires a wide footprint to which increases as height increases.
Environmental integration and sustainability	50	• Breaks waves stopping wave recoil disturbing ground Infront • Provides no location for life to settle.

Table 8(d): Design criteria evaluation concrete revetments

Design: Concrete Revetments		
Criteria	**Weighting out of 100**	**Justification**
Sea water and wave resistance	90	• Seawall is made of concrete and is resistant to salt water. • Slopes designed to reduce the force of wave impact.
Design life – durability	70	• Expected design life 30-50 years • Wall requires large earth works / area to be built therefore more expensive option. • Minimal maintenance needed due to concrete strength.
Aesthetics	35	• Normally very large slabs of concrete that take up a large footprint therefore very unappealing and hard to blend into foreshore.
Future Upgradability	80	• Wall can be easily constructed on top of revetment to provide additional height.
Material Availability	60	• Standard type of constructing for a seawall however will require large amounts of engineering and earth works as back fill.
Ease of construction	65	• Large amount of earthwork and concrete required for construction.
Footprint	50	• Requires a wide width for the slope where width increases proportionally to height.
Environmental integration and sustainability	50	• Slope minimising wave scouring damage to sea floor below. • Provides no location for life to settle.

Table 8(e): Design criteria evaluation rip rap revetment

Design: Rip Rap revetment		
Criteria	**Weighting out of 100**	**Justification**
Sea water and wave resistance	80	• Seawall is made of rocks resistant to salt water. • Rocks will break up impact of waves though less efficient than walls designed to do so.
Design life – durability	60	• Durability can vary depending on rock size and how often large waves crash against it.

		• Constant force from large waves can cause the rocks that makeup a rip rap revetment to move there needing maintenance. • Riprap is cheaper the other design solutions requiring less engineering however access is needed to many large rocks to create strong enough design.
Aesthetics	70	• If tied in correctly can give natural look to shoreline.
Future Upgradability	80	• Can be easily upgrades by stacking more rocks or building a vertical wall behind.
Material Availability	50	• If large rock collection location / quarry nearby can be easy to transport and construct. • Not ideal if no location near by then will have to transport large amount of material.
Ease of construction	90	• Relatively easy to construct requiring minimal engineering in comparison to other options
Footprint	50	• Requires a wide footprint which increases comparatively to increase in height.
Environmental integration and sustainability	80	• Creates cover for life and can crease small pools of water for aquatic life to remain at low tide.

Table 8(f): Design criteria evaluation natural shorelines

Design: Natural shorelines		
Criteria	**Weighting out of 100**	**Justification**
Sea water and wave resistance	20	• Sea water and waves and wash away natural shorelines over time as nothing to resist waves forces except bonds between soil/sand causing erosion.
Design life – durability	20	• Natural shoreline has minimal durability with erosion occurring with constant forces from waves or during storms. • If natural shoreline erodes seawalls design needs to be implemented to stop further reduction in shorefront.
Aesthetics	100	• Most natural looking design that fits in with Cairns reputation as an outdoor environment conscious nature based destination.
Future Upgradability	50	• As not construction completed upgrades can occur without having to deconstruct existing structure however there is also nothing to upgrade upon.
Material Availability	100	• No material required
Ease of construction	100	• No construction required
Footprint	30	• Large footprint needed between shoreline and any building constructed behind as no protection from waves during cyclone and nothing to stop erosion
Environmental integration and sustainability	100	• Natural environment perfect for all aquatic life currently inhabiting.

In Table 9 the weighting scores for each alternate seawall design are multiplied by the weighting factor for each selection criteria. The scores are averaged in the far-right column. The sea wall with the highest score is the best solution.

Table 9: Design weighting score evaluation

Seawall Design	Sea water & Wave Resistance	Design Life – Durability	Aesthetics	Future Upgradability	Material Availability	Ease of construction	Footprint	Environmental integration & sustainability	Weighting Score
Weighting Factor	0.34	0.22	0.13	0.1	0.06	0.04	0.05	0.06	1
Vertical Seawall	75	75	50	100	95	90	100	40	**75.2**
Curved Seawall	100	90	50	30	95	60	85	60	**79.25**
Stepped Seawall	90	75	60	90	95	60	80	50	**79**
Concrete Revetment	90	70	35	80	60	65	50	50	**70.25**
Riprap Revetment	80	60	70	80	50	90	50	80	**71.4**
Natural Shoreline	20	20	100	50	100	100	30	100	**46.7**

Example: Weighting score calculation for the vertical seawall:
$(75\times0.34) + (75\times0.22) + (50\times0.13) + (100\times0.1) + (95\times0.06) + (90\times0.04) + (100\times0.05) + (40\times0.06) = 75.2$

Calculations for other seawalls are contained in Appendix C.

5.7 Summary of results

The outcome of the AHP (Table 9) shows that the curved concrete seawall attained the highest relative weighting score of 79.25 indicating this is the best seawall choice for Cairns. This wall is the most resistant to sea water and wave impact, has a small foot print and construction materials are readily available. Although it is the most difficult to upgrade, it is the most durable and has the longest design life. When compared to a natural shoreline a curved concrete seawall is not aesthetically pleasing and does not and support environmental sustainability. However, this problem applies to other seawall types as well. A vertical curved seawall does not take up much space and is relatively unobtrusive. A wall of this type can be built with paths and seating on the top that overlooks the ocean. This will help it to blend in with the Esplanade parklands in a way that will not impact the aesthetics to much and therefore continue to support the tourist economy upon which Cairns relies.

The stepped and vertical seawalls also scored highly with scores of 79.25 and 75.2 respectively showing that these walls would also be a good choice for Cairns. The closeness of the scores is not surprising as they have a lot of similarities to the curved concrete seawall. The stepped seawall has a wider footprint that would dominate the view more and therefore make it less acceptable as it would not blend in with the Esplanade environment as well as a thin vertical wall.

The concrete and riprap revetment walls scored 70.25 and 71.4 respectively. The major disadvantage of revetment seawalls is their very wide foot print. Whilst not a major problem in areas where there is a lot of space, it is not ideal along the Esplanade. The area is environmentally sensitive and walls with smaller footprints are less dominating and fit better into the overall appearance and role of the Esplanade as a premier tourist destination.

A natural seawall (Chapter 3.12.3) is the most aesthetically pleasing, the best choice for environmental sustainability and the easiest to construct. These are important characteristics; however, this type of wall rates the worst for seawater/wave resistance, durability and the size of its foot print. A natural seawall will not do the job required along the Esplanade and therefore scored last at 46.7.

The AHP determined that a curved concrete seawall is the best solution along the Cairns Esplanade. The next chapter considers modular seawalls that can protect the Esplanade in the period before construction of a permanent sea wall is fully completed.

Chapter 6: Modular seawall - Analytical Hierarchical Process

6.1 Introduction

As discussed in the Implementation Considerations section (Appendix B), a solution to protecting Cairns is not as simple as just building a seawall and it will take a number of decades to fully implement the project. A seawall for the recently renovated southern section of the Esplanade is unlikely to be constructed for 20 to 30 years as it is only feasible as part of the next major redevelopment. In the interim, a modular flood wall that can be quickly constructed and deconstructed will be required. This chapter further addresses objective 2 and uses an Analytical Hierarchical Process (AHP) to evaluate the three modular seawall alternatives (Geodesign temporary flood wall, Flow Defence barrier and NoFloods barrier tubes) described in sections 3.6 to 3.8. The chapter begins by identifying evaluation criteria and then works through the AHP to identify the best modular wall solution to protect the Cairns Esplanade whilst awaiting the completion of a permanent seawall solution.

6.2 Criteria descriptions

6.2.1 Stability wave resistance

A modular wall for Cairns does not need to resist the impact of strong crashing surf waves. Cairns is located in the sheltered Trinity Inlet and is not normally impacted by any wave action. However, the wall must be able to maintain its structural integrity and withstand the strong winds generated by tropical cyclones and the choppy seas and small waves that occur when a cyclonic storm surge impacts Trinity Inlet.

- How well can the modular flood wall resist the forces placed on it by cyclonic winds and higher choppy seas associated with a cyclonic storm surge?

6.2.2 Height

A modular floodwall does not have the strength of a permanent seawall and is not expected to resist a severe storm surge event. However, severe events are rare. The higher the structure the better it is able to protect Cairns so height whilst still remaining functional is a key criterion.

- What is the maximum height of flood protection provided by the solution?

6.2.3 Adaptability

The temporary seawall must be capable of being constructed in various locations along the foreshore. This means it must have the ability to go around corners, buildings and infrastructure, up and down small inclines and over many different surfaces.

- How flexible is the design? Can it be curved, go around corners, up inclines and around or in-between infrastructure?

6.2.4 Construction time

The course of a cyclone is difficult to accurately predict until it is relatively close to the coast. The ability to construct the wall at short notice is very advantageous. Additionally, it is not safe to construct the wall once the cyclone has started to impact Cairns so a short preparation and construction time is crucial for the selected solution.

- How long does it take to construct the wall?

6.2.5 Manpower

The more manpower available the quicker any wall can be constructed. However, the smaller the crew required to construct the wall in the available time the better. It is logistically complicated to organise a large amount of people to construct the wall in a short time frame in emergency situations.

- How many people are needed to construct the wall in the available timeframe?

6.2.6 Storage compaction

The temporary seawall is likely to be required only occasionally and, in some years, not at all so it will be in storage the majority of the time. It will therefore be beneficial for the wall to be compact so it can be easily transported and stored.

- How compact is the wall for ease of storage and transport?

6.2.7 Cost

A modular seawall up to 1.2 km in length will be needed to protect the Southern section of the Esplanade. Additionally, any damaged sections may need to be replaced or fixed. The modular seawall must be affordable in the context of the timeframe required before a permanent solution is in place.

- How expensive is the modular retaining wall?

6.3 Criteria importance justification

Table 10 starts the process of allocating a numerical score to each criterion. Two criteria are compared at a time and a judgement made about their relative importance.

Table 10: Comparison of criteria pairs and allocation of an importance multiplication factor

Criteria 1	Importance Multiplication	Criteria 2	Importance Justification
Stability (Wave Resistance)	=	Height	**<u>Stability = Height:</u>** Stability and height are two features that are intertwined in determining the wall design. The higher the wall, the more

			protection offered, however, as height increases the structure becomes less stable. Both aspects are considered to be equal in importance.
Stability (Wave Resistance)	=	Adaptability	**Stability = Adaptability:** The wall needs to be adaptable to suit any location where it is likely to be needed. Additionally, it must be capable to do its job. Hence, it was determined that theses aspects are also equal in importance.
Stability (Wave Resistance)	*3	Construction Time	**Stability 3x more important than Construction time:** Though construction time is important, there is little point in having a wall that is quick to construct but lacks stability to resist water/waves hence it was determined to be less important.
Stability (Wave Resistance)	*7	Manpower	**Stability 7x more important than Manpower:** Stability is a key factor when determining the best option as without stability the design can't function. Manpower is important but less so as more people can be allocated while stability in the design can't be changed.
Stability (Wave Resistance)	*7	Storage Compaction	**Stability 7x more important than Storage Compaction:** Stability is a key factor in determining the best option as it is crucial to prevent failure of the wall. The ability to be stored in a compact form is useful but significantly less important that stability.
Stability (Wave Resistance)	*7	Cost	**Stability 7x more important than Cost:** Though cost is an important factor, the cost of buying a more expensive wall is marginal in comparison to the damage that would be caused to Cairns if it failed during an extreme weather event.
Height	=	Adaptability	**Height = Adaptability:** Height and adaptably are both key aspects in determining the best option. The wall will be needed in a range of locations and situations. Both were determined to be equally important.
Height	*3	Construction Time	**Height 3x more important than Construction time:** Height is a factor that cannot change after purchase of the wall. It is also a key criterion for protecting Cairns from inundation. Construction time can be decreased by adding additional personal to the construction team hence it was determined to be less important.
Height	*7	Manpower	**Height 7x more important than Manpower:** Height is a key factor in determining the size of waves/storm surge that can be resisted. However, manpower needed will just change the ease of construction hence was determined to be less important.
Height	*7	Storage Compaction	**Height 7x more important than Storage Compaction:** Height is a key factor in protecting Cairns from inundation. Ease of storage is far less important.
Height	*7	Cost	**Height 7x more important than Cost:** Height is a key factor in protecting Cairns from inundation. Cost of the wall is marginal in comparison to the damage cost if Cairns is flooded.
Adaptability	=	Construction Time	**Adaptability = Construction Time:**

			Adaptability is important but if it takes ages to construct the temporary wall is not very useful so both have been assessed as equally important.
Adaptability	*3	Manpower	**Adaptability 3x more important than Manpower:** Adaptability an important factor in choosing the design as it will determine the locations and situations in which the wall can be utilised. Lack of adaptability can stop a design from being capable of protecting a key area. Manpower can be easily increased so is considered less important.
Adaptability	*3	Storage Compaction	**Adaptability 3x more important than Storage Compaction:** Adaptability is an important factor as this determines the locations and situations in which the wall can be utilised. The ability for the wall to be stored in a compact form is far less important.
Adaptability	*3	Cost	**Adaptability 3x more important than Cost:** Adaptability determines the locations and situations in which the wall can be utilised. An adaptable wall that can be used in numerous situations can potentially save millions of dollars in prevented damage from flooding. The cost of the wall in comparison is negligible so therefore less important.
Construction Time	*2	Manpower	**Construction Time 2x more important than Manpower:** Constitution time and manpower are linked as increased manpower will lead to reduced construction time. However, construction time is the more important factor here as it will determined if the wall is ready in time for cyclone hence was determined to be more important.
Construction Time	*5	Storage Compaction	**Construction Time 5x more important than Storage Compaction:** A decreased construction time allows for the wall to be constructed with in the safe period prior to the arrival of the cyclone. This is much more important than whether the wall can be easily stored.
Construction Time	*5	Cost	**Construction Time 5x more important than Cost:** It is important that the wall can be constructing it in timely manner prior to the arrival of a cyclone. There is no point having a cheap wall that is ineffective because in cannot be constructed in time. Additional cost is a worthwhile investment to ensure the safety of workers.
Manpower	*5	Storage Compaction	**Manpower 5x more important than Storage Compaction:** The less manpower needed the better. Manpower is associated with construction time. This is important to ensure that the wall is ready prior to a cyclone arrival. Manpower is much more important than issues with storage.
Manpower	*5	Cost	**Manpower 5x more important than Cost:** The less manpower needed the better. Manpower is associated with construction time. This is important to ensure that the wall is ready prior to a cyclone arrival. There is no point having a cheap wall if it cannot be constructed in time. Therefore, manpower is more important than cost.
Cost	*3	Storage Compaction	**Cost 3x more important than Storage Compaction:**

			A lower cost makes it easier to justify the investment in the wall and perhaps how long a wall can be purchased. Storage also incurs costs. However, the damage costs from the city being inundated are much higher. Therefore, cost is more important than storage.

6.4 Weighting factor calculations

The relative importance of each criterion is converted into numerical value values and the sum of the values found (Table 11). The averages of each criterion are processed in a pair-wise matrix to find the criteria weighting factor (Table 12). An explanation of Weighting Factor Calculations and process can be found in section 5.4.

Table 11: Pair-wise comparison matrix

Pair-wise comparison matrix							
	Cost	*Storage Compatibility*	*Construction Time*	*Man Power*	*Stability (Wave Resistance)*	*Height*	*Adaptability*
Cost	1.00	3.00	0.20	0.20	0.14	0.14	0.33
Storage Compatibility	0.33	1.00	0.20	0.20	0.14	0.14	0.33
Construction Time	5.00	5.00	1.00	2.00	0.33	0.33	1.00
Man Power	5.00	5.00	0.50	1.00	0.14	0.14	0.33
Stability (Wave Resistance)	7.00	7.00	3.00	7.00	1.00	1.00	1.00
Height	7.00	7.00	3.00	7.00	1.00	1.00	1.00
Adaptability	3.00	3.00	1.00	3.00	1.00	1.00	1.00
sum	28.33	31.00	8.90	20.40	3.76	3.76	5.00

Table 12: Normalised pair-wise comparison matrix

Normalised Pair-wise comparison matrix								
	Cost	*Storage Compatibility*	*Construction Time*	*Man Power*	*Stability (Wave Resistance)*	*Height*	*Adaptability*	*Criteria Weights*
Cost	0.04	0.10	0.02	0.01	0.04	0.04	0.07	0.04
Storage Compatibility	0.01	0.03	0.02	0.01	0.04	0.04	0.07	0.03
Construction Time	0.18	0.16	0.11	0.10	0.09	0.09	0.20	0.13
Man Power	0.18	0.16	0.06	0.05	0.04	0.04	0.07	0.08
Stability (Wave Resistance)	0.25	0.23	0.34	0.34	0.27	0.27	0.20	0.27
Height	0.25	0.23	0.34	0.34	0.27	0.27	0.20	0.27
Adaptability	0.11	0.10	0.11	0.15	0.27	0.27	0.20	0.17
							Sum	1.00

Height and stability (wave resistance), both of which scored 0.27 out of 1, have been ranked as the most important selection criteria, whilst storage compactibility and cost are the least important.

6.5 AHP – Modular flood wall rating

Table 13 summarises the results of the pair-wise comparison matrix and ranks the criteria in order of importance. Questions that need to be asked to evaluate each alternative temporary flood wall against that selection criteria are shown. This provides transparency in the selection process.

Table 13: Criteria weighting factor and evaluation point summary

Criteria	Weighting Factor	Ranking	Temporary Wall Evaluation Points
Stability (Wave Resistance)	0.27	1	• How well can the temporary walls resist the forces placed on it by rising water pushing against it? • How will the wall perform against a choppy sea with small waves?
Height	0.27	2	• What is the maximum height provided by the solution?
Adaptability	0.17	3	• How flexible is the design? Can it be built as a curve, around corners, up inclines, and in-between infrastructure?
Construction Time	0.13	4	• Time needed for a standard sized crew to construct retaining wall?
Man Power	0.08	5	• Number of people needed for construction of the wall within reasonable timeframe.
Storage Compaction	0.04	6	• When not in use, how easy is it to store and how compact is it. How much space is required?
Cost	0.03	7	• How expensive is the modular retaining wall?
Total Weight Factor	1	-	-

6.6 Design option weighting justification and comparison

Tables 14(a) to 14(c) introduce each of the alternate temporary flood wall designs into the calculation process. Each alternate wall has its own table. The wall is assessed against each selection criteria and allocated a subjective score out of 100. The reasons for this judgement given in the 'Justification' column.

Table 14(a): Design criteria evaluation Geodesign temporary flood barrier

Design: Geodesign temporary flood barrier		
Criteria	**Weighting out of 100**	**Justification**
Stability (Wave Resistance)	50	The wall is effective in calm flood water but it is less clear how well it can handle strong winds and small waves.
Height	100	Comes in a range of heights: • 0.4m to 0.6m • 0.6m to 1.2m • 1.2m to 2.4m
Adaptability	60	The design can go around corners and up slopes but still needs flat terrain for construction and maximum efficiency.
Construction Time	60	200-300m long, 1.8m high wall constructed in Maryborough by a team of 30-40 people in around 6 hours.
Man Power	40	A large amount of man power is needed to construct the walls.

Storage Compaction	60	The wall is constructed in small sections that can be easily stored. However, a large space is still required to store all the components.
Cost	60	The cost varies depending on the height needed. Medium cost relative to other options.

Table 14(b): Design criteria evaluation Flow Defence

Design: Flow Defence		
Criteria	**Weighting out of 100**	**Justification**
Stability (Wave Resistance)	80	Being a stainless-steel barrier, it is expected to perform well against small waves. It relies on small lengths supported by strong concrete pillars at regular intervals.
Height	100	Barrier comes in a range of heights ranging from 300 to 2400mm in intervals of 100mm.
Adaptability	0	No adaptability is present in this design as it is installed in set locations.
Construction Time	100	No construction time needed as once installed it will raise automatically once flood waters reach it.
Man Power	100	No manpower required once installed as automatically raises as water levels rise.
Storage Compaction	100	As the wall is built into the earth no storage is needed as it ties in seamlessly with the ground its built on.
Cost	20	The cost for this wall is very high as the wall frame is buried in the ground and it also needs to be supported by concrete pillars to provide stability. Most of the cost is at installation with minimal ongoing maintenance costs.

Table 14(c): Design criteria evaluation NoFloods mobile flood barrier tubes

Design: NoFloods flood barrier tubes		
Criteria	**Weighting out of 100**	**Justification**
Stability (Wave Resistance)	70	The tubes are a proven flood barrier to stop the ocean encroaching inland and has the ability to absorb the impact of small waves. However then is no example of cyclonic winds and cyclonic waves pushing against the flood barrier tubes.
Height	70	Minimum Height 50cm Maximum Height 1.8m
Adaptability	90	The wall is very adaptable able to go up slops, around curves and corner with ease.
Construction Time	90	Very quick construction time as it can be rolled out using a forklift and just needs a pump to fill it with water. In an example scenario 1000m was deployed in less than 4 hours by 4 people and a small truck.
Man Power	90	Minimal manpower required. One or two people to deploy the tubes from a small truck and another couple of people to work the pumps to fill it with water.
Storage Compaction	80	Once empty the tubes are flat and easily rolled up for storage. The unit to be stored is very compact.
Cost	90	Least expensive option

In Table 15 the weighting scores for each alternate temporary flood wall are multiplied by the weighting factor for each selection criteria. The scores are averaged in the far-right column. The wall with the highest score is the best solution.

Table 15: Design weighting score evaluation

Temp. Seawall Design	Stability Wave Resistance	Height	Adaptability	Construction Time	Man Power	Storage Compaction	Cost	Weighting Score
Weighting Factor	0.04	0.03	0.13	0.08	0.27	0.27	0.17	1
Geodesign temporary flood wall	50	100	60	60	40	60	60	54.8
Flow Defence	80	100	0	100	100	100	20	71.6
NoFloods flood barrier tubes	70	70	90	90	90	80	90	85

Refer appendix C for weighting score calculation process.

6.7 Summary of results

Table 15 shows the outcome of the AHP. With a score of 85, the NoFloods barrier tubes is the best option for use as a temporary flood wall. Even though it did not score as well as other alternatives on height, its other strengths more than make up for this. It is very adaptable and it can be constructed very quickly with little manpower. This is very important when the time frame available for construction before a cyclone arrives may be very short. NoFloods scored consistently high across all evaluation criteria and was the clear winner.

The second choice, with a score of 71.6, was the Flow Defence wall that automatically raises with water pressure. This is a very good product for short spans. But for larger areas it needs to be supported with multiple concrete pillars. This makes it very expensive. It is also fixed in position so in not very adaptable.

The Geodesign wall scored 54.8. It has good height and worked well protecting downtown Maryborough from flooding in early 2022. However, it took a lot of time and manpower to construct. This is a major drawback. Cyclones can change speed and direction leaving little time to construct before they arrive. Additionally, it is not certain how it will perform against choppy sea water.

The NoFloods barrier tubes are clearly the best temporary floodwall solution for Cairns.

Chapter 7: Conclusion and recommendations

The objective of this research project was to identify engineering solutions to protect Cairns from inundation due to cyclonic storm surge and sea level rise. This report evaluated different types of seawalls through and Analytical Hierarchical Process (AHP). The AHP results show the following:

- Curved concrete seawall ranked the highest at 79.25
- Stepped concrete seawall ranked a close second at 79
- Vertical concrete seawall ranked third at 75.2
- Riprap revetment ranked fourth at 71.4
- Concrete revetement ranked fifth at 70.25
- Natural shoreline ranked last at 46.7

With the highest score of 79.25, a curved concrete seawall is recommended as the best solution to protect Cairns from inundation.

The southern part of the Esplanade has recently undergone a major redevelopment. A permanent seawall is not likely to be constructed along this section until the newly renovated boardwalk is due for replacement. The report therefore recommends that a modular flood wall, that can be constructed and deconstructed at short notice, be purchased to protect this section until a more permanent wall is built. The AHP results for temporary flood walls show the following:

- NoFloods barrier tubes ranked the highest at 85.
- Flow Defence barrier ranked second at 71.6
- Geodesign flood barrier ranked last at 54.8

With the highest score of 85, the NoFloods barrier tubes is recommended as the best temporary wall solution to protect the southern part of the Esplanade until a permanent wall is constructed.

Whilst sea level rise is going to occur slowly over many decades, the city already regularly floods during king tide events and narrowly escaped catastrophe in 2011 when a cyclonic storm surge arrived at low tide. The city is therefore under threat now. It is only through luck that Cairns has not experienced a major catastrophe. The risks continue to increase each year and it is a matter of time before the city's luck runs out. If Cairns floods, the majority of the inner city will be severely impacted on a scale that has never been experienced in Australia. This includes the Esplanade tourist strip, international hotels, hospital, schools, airport, seaport, CBD, shopping centres, businesses, industrial area and residential suburbs. All of Cairns most critical infrastructure areas will be devastated. The Cairns economy will be destroyed and will take many years to recover. The consequences for the people of Cairns are extreme. In comparison, the costs of implementing the recommendations of this report are small. The Cairns Esplanade is the primary social and economic driver for the city. The southern section has recently undergone a major redevelopment. It is therefore likely that a seawall project will need to be implemented in stages over an extended period of time to minimise disruption and fit in with future redevelopments. It is therefore important that planning and action to implement the initial stages of the seawall project commence immediately.

7.1 Limitations and further study

A significant limitation of AHP is that the weighting scores are subjective. The importance of each selection criteria needs to be discussed and agreed upon so a weighting score can be allocated. The importance of each criterion could be changed at a later date. This may change the AHP outcome.

Another limitation is that the scope of this research project is limited to being an initial study that clearly establishes the extent of the problem and identifies the best solution. The specific technical aspects and design specifications required to construct the curved concrete wall have not been determined. Additionally, machinery and material quantities, funding requirements, timeframes and the scope of the final project (including raising or reclaiming land) would all need to be established in a future study.

7.2 Implementation considerations

The literature research (Chapter 3) identified that construction of a seawall cannot be considered in isolation. Rather, the seawall needs to be part of a broad range of complimentary solutions that work together to protect Cairns from coastal inundation. This includes management of the water catchment the builds up behind the wall, hardening infrastructure, and raising the floor levels of new buildings.

Maintaining the attractiveness of the Esplanade and parklands as well as connection to the ocean is crucial to retain the city's reputation as a premier tourist destination. It is particularly important that the seawall does not negatively impact the tourism industry and the city's future economic prosperity.

The research completed included examples where reclaiming and raising land were included as part of seawall projects. The seawall becomes the front edge of the reclaimed or raised land. Reclaiming and raising land along the Cairns Esplanade would be very useful in maintaining the city's aesthetics, connection with the ocean as well as creating space for future development. It is therefore recommended that the seawall project be combined with reclaiming and raising land. A discussion on how this might be achieved, possible time frames etc. has been included as Appendix B.

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Appendices

Appendix A – AHP calculations

Appendix B – Implementation considerations

Appendix C – Project specification

Appendix D – Project methodology

Appendix E – Resources

Appendix F – Project schedule

Appendix G – Quality assurance and risk management plan

Appendix A – Project specification

ENG4111/4112 Research Project

Project Specification

For: Grant O'Donoghue

Title: **Engineering solutions to protect Cairns from coastal inundation due to storm surge and sea level rise**

Major: Civil Engineering

Supervisors: Allan Manalo

Enrollment: ENG4111 – EXT S1, 2021

ENG4112 – EXT S2, 2021

Project Aim: To comparatively evaluate different engineering solutions and to identify most suitable engineering solutions that will protect the Cairns Esplanade from sea level rise and cyclonic storm surge inundation whilst maintaining its tropical aesthetics and ensuring the city can still prosper as a premium tourist destination.

Programme: Version 1, 02th March 2022

1. Review of available literature on impact of cyclones and sea level rise on infrastructure with specific considerations to the geography of Cairns.
2. Research worldwide strategies to manage coastal inundation and cyclonic storm surges and identify examples of possible solutions for the Cairns Esplanade focusing on innovative and realistic options.
3. Conduct an analytical hierarchical process evaluation for potential solutions to down select up to five well suited potential solution for Cairns in terms of parameters including practicality, ease of implementation, future upgradability, and aesthetics.
4. Detailed analysis of the down selected top 5 solutions in terms of cost of installation, material availability, material volumes and short/medium/long term time frames for implementation of each aspect.
5. Propose an incremental plan of the ideal option for the Cairns Esplanade, with all necessary justifications, that can be incorporated into future town planning guidelines.
6. Prepare and submit a high quality dissertation.

If time and resource permit:

1 Include alternative options for protecting the Cairns Esplanade.

2 Expand the plan to incorporate different options that could be suitable for nearby locations such as the CBD and airport.

The aim of the research project is to develop specific engineering solutions that will protect Cairns Esplanade from sea level rise and cyclonic storm surge inundation whilst maintaining its tropical aesthetics and ensuring the city can still prosper as a premium tourist destination up to 2100 and beyond.

Cairns is an extremely low lying city and will be amongst the first in the world to face the threat of climate change induced sea level rise. Some city streets already flood at king tide. An expected sea level rise of 0.8m by 2100 will see much of the high value commercial, industrial, airport, seaport, CBD and tourist areas, as well as the higher density inner city residential suburbs, below the normal tidal range and regularly inundated. The city narrowly escaped catastrophe in 2011 when Cyclone Yasi threatened to send 2m of cyclonic waters crashing through the tourist strip and into CBD buildings. Luckily Cairns missed out on the worst of the cyclone and the associated storm surge arrived at low tide. Despite this warning, little has been done to protect the city. The risk of catastrophic inundation will increase significantly as sea levels rise and severe tropical cyclones become more common.

There is no simple solution. It will require a holistic understanding of the many issues and a complex combination of innovative solutions that minimise disruption, evolve over time and can be implemented incrementally over decades as the threat increases. The first step is to identify options, create a plan of what needs to be done in the short, medium and long terms, and get the process started so solutions can be incorporated into town planning and future budgets.

As well as having a personal interest in protecting my home town, I believe protecting all our coastal cities from climate induced sea level rise will be one of the greatest challenges facing engineers in the decades ahead. This project is of great interest to me and will potentially be very important in my professional development as a future engineer in Cairns.

Appendix B – Implementation considerations

The learnings from Chapter 3 show that protecting Cairns from sea level rise and cyclonic storm surges is not just about building a seawall. There are many other considerations including the opinions of residents and impact on the local economy. Complimentary solutions that take this into consideration and should be incorporated into an overall plan rather than building a seawall in isolation include:

- Catchment water being trapped and needing to escape from behind the seawall.
- Incorporating gates on drains/creeks that close at low tide to stop extreme tides and storm surges flowing up drainage systems to flood the city behind the wall (small version of the Thames Barrier).
- Constructing/retaining green zones within the city to soak up excess rain water that builds up behind the wall.
- Creating and maintaining natural buffer zones to block the ocean (enhanced natural shorelines and mangroves).
- Opportunity to reclaim land (Netherlands).
- Raising land – instead of a thin wall, raise the whole area and build on top (Japan).
- Landscaping to block wave run up (mounds, raised garden beds, small walls, seating).
- Hardening infrastructure to cope with inundation (raised ground floors).

B1.1 Control of the water catchment behind the seawall

Located in the far north of Australia, Cairns is impacted by the annual tropical monsoon season. This means the city has defined wet and dry seasons. Average rainfall is usually around 2 metres per year (BOM 2022). The vast majority of this falls in the wettest three months from January to March. The mountains behind Cairns channel large amounts of water through the open waterways and creeks that run through the city (Figure 1(a)). Building seawalls and levees around the city to protect against storm surge and sea level rise has the potential to block this drainage system and turn the area behind the wall into a large lake during extreme rainfall events.

Most creeks flow into two main open drainage waterways, one to the north and one to the south of the city. Similar to the sluice gates of the Oosterschelderkering barrier in the Netherlands (Chapter 3.2.), though on a much smaller scale, gates must be placed at the outflow of these two drains (1 and 2 on Figure 1). These gates would be closed at low tide, prior to king tide and cyclonic storm surge events, to prevent the tide surging up and filling the inner-city waterways. This allows space for rainfall and stream flow to collect without flooding the city. The collected water is released at the next low tide.

Figure 1(a): Hill slope streams flow into open drainage waterways that run through Cairns. Gates are required at locations 1 and 2 to prevent tidal surges flowing up the waterways and flooding Cairns.
(Source: Cairns Regional Council, Cairns Plan 2016)
Figure 1(b): Cairns City remnant swamps act as huge sponges, soaking up excess rainfall.
(Source: Google Earth 2022)

Cities in the Netherlands (Chapter 3.2) have also created green spaces such as parks, natural areas and green rooftops to absorb and hold excess rainfall in order to prevent flooding of the city during high rainfall events. Additional capacity has been created by designing public infrastructure like basketball courts to act as water retention areas. Cairns already has several remnant swamps in the inner-city area that fulfil the same function (Figure 1(b)). The importance of these swamps as water retention areas needs to be recognised. These swamps should be maintained and not developed.

Other than tidal surge gates at the outlets of the main drainage waterways and smaller gates on other city drains, no other infrastructure is required to manage the water catchment system behind the Cairns central city area.

B1.2 Reclaimed and raised land

As far back as 1953 land started to be reclaimed at the southern end of the Esplanade when mud and silt spoil from the harbour dredge "Trinity Bay" was dumped on the site. Overtime the size of the reclaimed land grew (Figure 2(a)) and in 1989 the Pier Market place shopping centre, hotel complex and marina were opened on the site. Further land was reclaimed over 2002, which became the site of the Cairns swimming lagoon and parklands (Figure 2(b)). The area has become the focal point for tourists and much of the city's tourism infrastructure is located on or in the immediate vicinity of this reclaimed land.

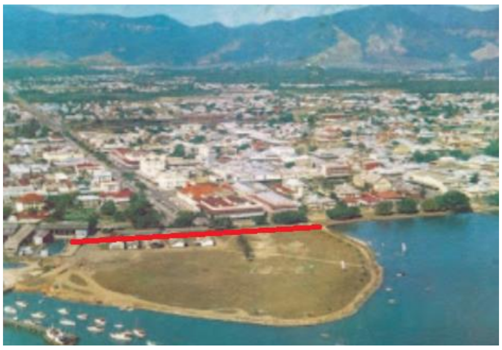


Figure 2(a) and 2(b): Land reclamation started along the southern part of the Esplanade in 1953 and today holds important tourism infrastructure (Source: Moore 2012 and Cairns & Great Barrier Reef 2022)

More recently, in 2014, the Cairns Regional Council built a 1.3 km rip rap seawall in the suburb of Machans Beach (Chapter 3.4). The wall was built a further 6 m out from the shoreline. The reclaimed land allowed for a wider road along Oshea Esplanade, narrow parklands and a walkway to be constructed along the length of the wall to create an attractive foreshore recreational area for the suburb. The council also took the opportunity to raise the level of the land in the immediate vicinity of the wall. In the lowest areas, the wall is now about 1 m higher than the previous ground and road level with an additional 0.4 m in height gained from the rock wall being higher again (Figure 3).

Figure 3: The Machans Beach seawall constructed in 2014, reclaimed about 6 m of land from the ocean and raised the ground level next to the wall in some areas by around 1 m (O'Donoghue 2022)

The success of these local examples demonstrates that the opportunity to reclaim and raise land should also be considered as part of the seawall project.

According to the Queensland Government Statistician's Office (2021), the population of Cairns as at 30 June 2021 was 168,853. By 2041 it is expected to be 236,593. This is an increase of 67,740 (40%) over 20 years (Queensland Government Statistician's Office 2021). Even with the recent improvements, the popular southern section of the Esplanade is often overcrowded. As the population and visitor numbers increase the obvious area for expansion is the quieter northern section of the Esplanade. To create space for this expansion the northern seawall should be built in line with the southern seawall. This would allow for 1.2 km of land to be reclaimed from the ocean along the northern Esplanade (Figure 4).

Figure 4: The building of a seawall offers the opportunity to reclaim 1.2km of land along the northern part of the Esplanade (Google Earth 2022)

Similar to how land was previously reclaimed, the mud and silt that makes up the mudflats can be pumped on to the area to be reclaimed and allowed to settle. Over this period the parkland behind the reclaimed area would remain accessible. Although the view would be temporarily interrupted there would be little disruption to the public.

If land is being reclaimed it would also make sense to raise the height of the newly reclaimed land by at least 1.2 m to match the seawall that would front the shoreline. After the newly reclaimed and raised land had settled, new parklands would be established on top which maintains the ocean views in the decades ahead. The new parklands are considerably larger and would therefore be able to cater for increased population and visitor numbers.

This then raises the question about what should be done with the current parklands? This stable land would be suitable for building future resorts, hotels, bars, restaurants and cafes (Figure 5) to take the pressure off the southern section of the Esplanade. In 20, 30 or 40 years time, when the demand for these additional facilities will exist, the land will be ready and waiting and the new parklands would have matured. The value of these park and ocean facing blocks of land, right in the tourist and commercial centre of Cairns will be very high. The proceeds of land sales would go a long way to funding the cost of reclaiming land and building the seawall as well as catering for and encouraging future tourism growth.

Figure 5: In future decades the old parklands along the northern explanade would allow the for the expansion of the tourist industry and support the future economy of Cairns (Google Earth 2022)

B1.3 Hardening buildings against inundation

The transformation of Cairns into a premier international tourist destination accelerated with major hotel developments in 1987 and 1989 and the opening of the Cairns International Airport in 1990. Most of the tourist infrastructure, including the Esplanade dining precinct, lagoon and boardwalk and marina is located along the southern section of the Esplanade and on the reclaimed land at the southern end of this area. This southern section of the Esplanade has therefore become the social and tourism centre of Cairns.

B1.31 Raised buildings

The Pier shopping centre and hotel complex is a land mark building in Cairns that was built on reclaimed land in 1989. It hosts numerous restaurants and bars on the wide open-air verandas that surround the building on two sides and overlook the marina and Esplanade. The ground floor and verandas are raised 1.7 m above ground level (Figure 6). This height offers great views but the complex was most likely built this way to minimise the depth needed to accommodate the large semi-underground car park.

Figure 6: Ground floor of the Pier Shopping Centre raised 1.7m (O'Donoghue 2022)

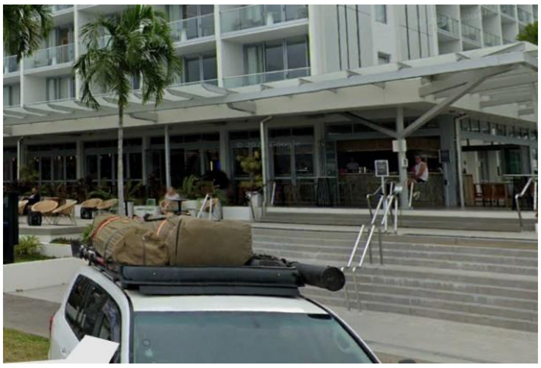
The first floor of the neighbouring Hilton Hotel, built 1987, has also been built on top of a semi-underground car park (Figure 7). However, the Hilton Hotel also has a popular café/bar at the natural ground level to take advantage of its unique location directly in front of Trinity Inlet. The risk to infrastructure built at ground level was shown in 2014 when there was an unusually high king tide event.

Figure 7: The ground level of the Hilton Hotel is built above a semi-underground car park whilst the café/bar fronting Trinity Inlet is at normal ground level (Google Earth 2022)

Superficial flooding in the lowest areas around Cairns occurs a couple of times each year when regular king tide events cause sea water to well up though the drains. However, some king tides are higher than others and come dangerously close to inundating the whole CBD and Esplanade area. Figures 8(a-b)) show the 2014 king tide event which flooded the Hilton Hotels ground level café/bar and underground car park along with nearby streets. However, raising the ground level of the hotel itself offered crucial protection against this flooding and allowed the hotel to continue operating with little interruption.

Figures 8(a) and 8(b): The king tide of 2014 inundated the Hilton Hotels café/bar and streets surrounding the Cairns Casino Hotel (ABC 2014)

The vast majority of Cairns buildings are older and built at natural ground level so are very susceptible to flooding. Most newer buildings are raised by at least a step or two. The inconsistent ground levels do not seem to be a problem and they do not look out of place amongst the varied ages and styles of buildings. The authors observations of the area are that, generally, the newer the building, the higher its ground floor level. The most recent buildings constructed are two Crystalbrook hotels built in 2019. The ground floor of one hotel has been raised by 0.97 m whilst the second is 1.2 m (Figures 9(a) and 9(b)).



Figures 9(a) and 9(b): Raised ground floor level in two Crystalbrook Hotels constructed 2019 (O'Donoghue 2022)

Most social venues offer signicant outdoor space to take advantage of Cairns warm tropical evenings. In addition to the usual street level seating and dining on the extrawide footpath, Crystalbrooks 'Flynn' Hotel has a raised ground level that is open to the street. This creates a vibrant social scene (Figure 10) that is caters for the large numbers of tourists and locals that frequent the Esplanade.

Figure 10: Crystalbrooks Flynn Hotel has street level seating and a raised ground floor that is open to the street providing a vibrant hive of activity (Crystalbrook 2022)

B1.32 Ageing buildings and recent development

Many old two-story buildings that made up the city's historical tourist infrastructure, still remain along the Esplanade to this day. As the Esplanade becomes more developed these simple buildings are being replaced by large multistory modern complexes (Figure 11).

Figure 11: The Esplanade consists of a mixture of old two-story buildings and more modern high-rise complexes (O'Donoghue 2022)

The popularity of the Esplanade precinct means that it is often very crowded and obtaining street side seating became increasingly difficult. To address this, the Cairns Regional Council recently undertook a $28m redevelopment of the southern Esplanade dining precinct. It was decided that access by general traffic along this part of the Esplanade was no longer safe due to the large number of people that frequented the area. The road was narrowed to one slow curving lane that allows access by commercial vehicles only. This allowed increased space for gardens and grassed areas, as well as the widening of the roofed footpath to cater for increased streetside dining. The new dining precinct opened in 2021 and provides a much improved, aesthetically pleasing, social centre (Figure 12) that is alive with activity and will serve Cairns well for many years to come.

Figure 12: Newly renovated Esplanade dining precinct (Commercial Real Estate 2021)

However, the redevelopment made no attempt to future proof Cairns against rising sea levels and inundation from storm surge. With the floor level of many of the buildings in this precinct already raised up a couple of steps the opportunity to raise the level of the footpath and road to match was not taken.

This could easily have been achieved and would have resulted in a step down into some of the older buildings rather than the step up that currently exists into the newer buildings.

The previous major development of the Esplanade occurred in 2003. The construction of the Cairns lagoon, parklands and iconic 550 m timber boardwalk has contributed much to creating Cairns reputation as a premium tourist destination. However, Cairns hot, tropical, wet and humid weather caused the boardwalk to deteriorate faster than expected and after only 12 years the heavy timber planks started to rot and fall apart. The planks have been replaced in the last few years at a cost of $2.5 million. Improved choice of wood, construction techniques and regular applications of weather resistant oil are expected to significantly increase the longevity of the boardwalk.

The cost and recency of these developments means that it is not be feasible to implement major changes that improve the resilience of the southern section of the Esplanade in the near future. The next opportunity will be at the time of the next major redevelopment in 20 to 30 years time. This delay is not necessarily a problem as the risk from sea level rise will increase slowly over many decades. Likewise, the solution to protect Cairns will also take many decades to fully implement.

In the meantime, council should work on putting gates on all drainage outlets to prevent backflow up the drains causing flooding during king tide events. Additionally, many of the ageing buildings along the Esplanade will be pulled down and redeveloped over the next 20 to 30 years. The design of these future buildings should be in line with the new Crystalbrook hotels and incorporate a ground floor level at least 1.0 m above the current footpath level.

B1.4 Raising the ground level of the southern Esplanade

In 20-40 years time the Cairns lagoon, boardwalk and dining precinct of the southern Esplanade will look worn, tired and dated. They will no longer fulfil their function as a major tourist drawcard. Another major redevelopment will be required. When this redevelopment occurs, action must also be taken to flood proof this section of the Esplanade.

When it comes time to replace the popular boardwalk, the replacement should be 1.2 m higher than the old boardwalk. The old concrete retaining wall underneath the boardwalk can be left in place. A new, properly engineered seawall, also 1.2m higher than the old wall, should be built just in front of the old wall. The new boardwalk would be built over top of the new seawall resulting in a boardwalk that looks very similar to current boardwalk, except 1.2 m higher.

As previously discussed, many of the old Esplanade buildings would be due to be replaced, or would already have been replaced by this time with their ground floors at least 1 m higher to match the two Crystalbrook hotels. Once this had happened, it would then be possible to also raise the thin 40 m wide strip of parklands and road between the raised boardwalk and raised buildings (Figure 13). The parklands may be raised first with slopes and small walls linking the raised parklands to the still low road. The road would be raised once all buildings in each block had achieved the required 1 m height. There are three blocks (Figure 13) in this section of the southern Esplanade. To minimise disruption, one block would be completed at a time. Once work was fully completed the whole area would have been raised by 1 to 1.2m. This would mean the views and connection to the ocean would be maintained as they are currently rather than being hidden behind a seawall.

Figure 13: The three tourist blocks of the southern Esplanade (Google Earth 2022)

This progressive raising of seawalls, land and building levels can repeated as a normal part of future major developments and into the next century to match long term rises in sea level.

B1.5 Temporary flood protection

Because action to construct a seawall on the southern Esplanade will not be possible for 20 to 30 years, council should first focus on reclaiming and raising land along the northern Esplanade and building the levee embankments on each side of the seawall. With these tasks completed Cairns would be protected from large king tides and cyclonic storm surge except for the gap created by the southern Esplanade section. The southern section could be protected by a 1.3 km temporary NoFloods mobile flood barrier as discussed in chapter 3.8 (Figures 14(a-b). This barrier can be quickly constructed before a large king tide or cyclone impacts the city and then quickly deconstructed after the event until it is required again.

Figures 14(a) and 14(b): The NoFloods mobile flood barrier can be quickly constructed to protect from large king tides or cyclonic storm surge (Bluemont 2022)

B1.6 Parkland features

Observations of the Esplanade parklands is that they do not consist completely of open flat land. Instead, there is a multitude of raised features and design elements that add interest, safety and practical comfort. These include grassy mounds, raised garden beds, seating and numerous walls that define various areas such as Muddies Playground and the skate park. Raised garden beds and wall elements are also a feature of the new dining precinct. Many of these features would be useful for hardening infrastructure. Structures like those shown in Figure 15 impede and break up any waves that that may otherwise crash into Esplanade buildings should the seawall be overtopped by a large storm surge. Consideration should be given to constructing these features in strategic locations all along the Esplanade.

Figure 15: Raised features and design elements impede wave run up in the event of overtopping of the seawall (O'Donoghue 2022)

The use of mounds and raised garden beds also offers the opportunity to plant and grow trees 1 m above current ground levels many years prior to the raising of the parklands. When the ground level of the parklands is eventually raised to the same level as the mounds and garden beds, mature trees will already be established and in place thereby maintaining the shady natural look of the parklands.

The restoration of Cardwell's foreshore after Cyclone Yasi in 2011 (Chapter 2.3) offers insight into design features that could be incorporated into the Cairns seawall. A basic rip rap rock armour revetment seawall was chosen for Cardwell. Similar to Cairns, a walkway and narrow parklands extend all the way along the length of the wall. In addition, variations such as lookouts (Figure 16) and a small pier jutting out into the water have been included at strategic locations to break up the wall and add interest.

Figure 16: A lookout adds a point of interest along Cardwell's foreshore (Watson 2014)

At the most prominent location, a tiered amphitheatre type structure was created (Figure 17). The different levels, textures and building materials make this section particularly interesting. Access is available to a small sandy beach providing direct connection with the ocean. Raised concrete seating at the top of the structure (Figure 18) would act as an additional wall blocking wave run up should this part of the wall be overtopped again.

Figure 17: An attractive amphitheatre structure has been included as a feature that breaks up Cardwell's rip rap rock armour seawall (Watson 2014)

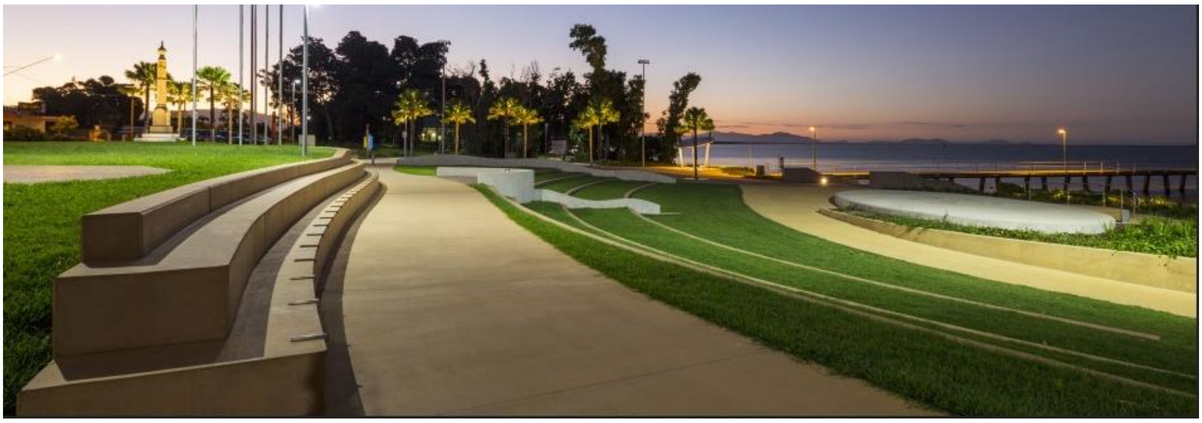


Figure 18: Raised concrete seating at the top of the amphitheatre structure acts as another wall to block wave run up if the ocean reaches this level (Watson 2014)

The Cairns Masterplan 2019 does not incorporate any features to combat sea level rise. However, it does emphasis making the most of the Esplanade's natural features and parklands to attract tourists and locals. This includes a boardwalk at the northern most end of the Esplanade to showcase and allow access to the mangrove forest (Figure 19). This would provide a fitting destination at the northern end of the seawall project

Figure 19: A boardwalk showcasing the mangrove forest at the northern end of the Esplanade Seawall was proposed in 2019 Cairns Masterplan (Cairns Regional Council 2019)

B1.7 Time frame

Due to the scale and cost of the project as well as the disruption to the Cairns tourist industry, the project would need to be completed in stages over several decades. In addition, reclaimed land takes several years to settle and the southern section of the seawall will not be able to be built until the recently renovated boardwalk in due for replacement in 20 to 30 years. The inundation threat to Cairns will grow significantly over this time so it is important to start the process of protecting the city now. A suggested timeframe for the various stages of the project is below:

0-10 years

- Construct gates on all drains to prevent backflow from king tides
- Commence reclaiming land northern Esplanade
- Commence building levee embankments
- All new buildings along the Esplanade raised by 1.0 m
- Commence planting new trees in raised garden beds or mounds along southern Esplanade

10-20 years

- Build seawall along settled reclaimed land Northern Esplanade
- Create parklands on top of reclaimed land Northern Esplanade
- Build large gates on the two main open drainage waterways to control backflow into the water catchment area.
- Purchase temporary NoFlood wall to close the gap along the Sothern Esplanade

20-40 years

- Replace southern boardwalk and raise by 1.2m
- Build vertical concrete seawall under new boardwalk
- Raise southern Esplanade parkland to match the new boardwalk
- Raise the road to match the level of the parkland once ground floor of buildings match

Appendix C – AHP calculations

Permanent seawall weighting score calculations:

Vertical Seawall

$$75 \times 0.34 + 75 \times 0.22 + 50 \times 0.13 + 100 \times 0.1 + 95 \times 0.06 + 90 \times 0.04 + 100 \times 0.05 + 40 \times 0.06 = 75.2$$

Curved Seawall

$$100 \times 0.34 + 90 \times 0.22 + 50 \times 0.13 + 30 \times 0.1 + 95 \times 0.06 + 60 \times 0.04 + 85 \times 0.05 + 60 \times 0.06 = 79.25$$

Stepped Seawall

$$90 \times 0.34 + 75 \times 0.22 + 60 \times 0.13 + 90 \times 0.1 + 95 \times 0.06 + 60 \times 0.04 + 80 \times 0.05 + 50 \times 0.06 = 79$$

Concrete Revetment

$$90 \times 0.34 + 70 \times 0.22 + 35 \times 0.13 + 80 \times 0.1 + 60 \times 0.06 + 65 \times 0.04 + 50 \times 0.05 + 50 \times 0.06 = 70.25$$

Riprap Revetment

$$80 \times 0.34 + 60 \times 0.22 + 70 \times 0.13 + 80 \times 0.1 + 50 \times 0.06 + 90 \times 0.04 + 50 \times 0.05 + 80 \times 0.06 = 71.4$$

Natural Shorelines

$$20 \times 0.34 + 20 \times 0.22 + 100 \times 0.13 + 50 \times 0.1 + 100 \times 0.06 + 100 \times 0.04 + 30 \times 0.05 + 100 \times 0.06 = 46.7$$

Modular seawall weighting score calculations:

Maryborough temporary flood wall

$$50 \times 0.04 + 100 \times 0.03 + 60 \times 0.13 + 60 \times 0.08 + 40 \times 0.27 + 60 \times 0.27 + 60 \times 0.17 = 54.8$$

Flow Defence

$$80 \times 0.04 + 100 \times 0.03 + 0 \times 0.13 + 100 \times 0.08 + 100 \times 0.27 + 100 \times 0.27 + 20 \times 0.17 = 71.6$$

NoFloods mobile flood barrier tubes

$$70 \times 0.04 + 70 \times 0.03 + 90 \times 0.13 + 90 \times 0.08 + 90 \times 0.27 + 80 \times 0.27 + 90 \times 0.17 = 85$$

Appendix D – Methodology

The purpose of this research paper is to identify and present strategies, options and a recommended solution to inform Cairns City Council planners, engineers and decision makers on the best engineering solutions to manage the impending threat of inundation from cyclone induced storm tides and climate change induced sea level rise.

There is no simple solution to this problem. This is especially because of Cairn's status and economic reliance on being a premium tourist destination. It will not be acceptable to build a view obstructing, unattractive seawall in front of the tourist strip that succeeds in protecting the city but results in the loss of what makes Cairns a special place. A far more innovative and aesthetically pleasing combination of solutions will need to be found. This will require a holistic understanding of the many issues and a multi-faceted response that evolves over time and can be implemented incrementally as the threat increases.

To achieve this the project will be carried out in three phases:

1. Project preparation and background research.
2. General Analytical Hierarchical Evaluation.
3. Detailed Analytical Hierarchical Evaluation and recommended plan.

If time permits a fourth phase will be included:

4. Alternative options and incorporation of nearby locations into protection plan (if time permits).

A description of individual tasks associated with each of phases is detailed below.

Table 1: Project tasks

Phase 1	**Project preparation and background research**
1A	Initial background research into the problem – The threat to Cairns due to inundation from cyclonic storm surges and sea level rise. This includes an Initial field study (on ground scoping survey) to become familiar with the general area, assess current situation/risk in relation to buildings, roads, infrastructure and identify solutions already in place. Form initial views on priority areas, possible adaption strategies. Identify available open space for hard engineering solutions.
1B	Research coastal inundation mitigation strategies to identify how the problem is being addressed around the world.
1C	Compile a comprehensive list of realistic options.
Phase 2	**General Analytical Hierarchical Evaluation**
2A	Determine appropriate evaluation categories and weighting.
2B	Category justification.
2C	Perform initial analysis and rank options.
2D	Identify top five solutions.

Phase 3	Detailed Analytical Hierarchical Evaluation
3A	Determine appropriate evaluation categories and weighting.
3B	Category justification.
3C	Perform a detailed analysis of top five solutions
3D	Present the recommended solution/plan.
Phase 4	**Alternative options and nearby locations (if time permits)**
4A	Identify and present alternate options.
4B	Extend recommended solution/plan to include nearby locations.

Appendix E – Resources

As this is primarily a literature research project the main resource requirement is personal time. Although difficult to accurately estimate, it is important to have some parameters as a way of monitoring progress against the final completion deadline of 13 October 2022. I have therefore been guided by the subject guidelines for ENG4111/4112, though note these are indicative estimates only:

40	Preliminary scoping study and related study
170	Project work
80	Report writing
30	Supervisor consultation
320	Estimated hours to complete the project

Research will be conducted using online sources to build upon work already completed as part of the Cairns Coastal Hazard Adaption Strategy (CHAS) report. This report and other resources such as satellite images, contour, flood and catchment maps and information on worldwide inundation projects are readily available online. The physical resources required (Table 3) are restricted to standard office equipment and stationary supplies.

A car is required as transport to complete the field studies in the Cairns area and a camera to record and illustrate practical aspects for the final plan. The expense of travel to Cairns has not been included as travel to my home town over semester break is not an additional expense.

Table 1: Resource requirements

Resource	Quantity	Source	Cost
Car	1	student	$20 petrol
Camera	1	student	nil
CHAS plan	1	Cairns Regional Council	nil
Satellite photos	1	Google Earth	nil
Contour and flood maps	several	Cairns Regional Council	nil
Catchment map	1	Cairns Regional Council	nil
Computer	1	student	nil
Internet access	1	student	minimal
MS Word	1	student	nil
Stationary/printing	as required	student	minimal

Appendix F – Project schedule

The idea for the project was started to be developed over semester 2 2021 as part of ENG4110 Engineering Research Methodology. A formal project proposal form was completed on 12 January 2022. Negotiation of the project topic, aspects to be included and the timeline for completion was finalised and approved at the start of March 2022.

An initial field study was completed in January/February 2022 whilst on location in Cairns. The purpose of this on ground scoping survey to further develop and consolidate the idea for the project and become familiar with the general area, assess the current situation/risk in relation to buildings, roads, infrastructure etc. so I could continue the project whilst based in Toowoomba.

The first phase of the project consists of extensive background research into the nature and extent of the threat to Cairns due to inundation from cyclonic storm surges and sea level rise. This is followed by further research in to coastal inundation mitigation strategies to identify how the problem is being addressed around the world. From this a list of all realistic mitigation options is to be compiled.
The first phase of the project was scheduled for completion by 8 May 2022 and is close to fully complete.

The second phase is an initial analysis and evaluation of all options to determine what solutions might be most appropriate to adapt to Cairns. This includes analysing and evaluating various types of seawalls through an analytical Hierarchical Evaluation ranking process to identify the top five solutions. Initial analysis has commenced and is expected to be completed by 3 July 2022 as per the schedule.
A further field study is required during the mid-semester break commencing 20 June 2022 to determine the practicality of solutions and finalise the route/location of a future seawall.

The third phase of the project will be completed during semester 2 2022 the top five solutions will be evaluated more in-depth and will then be adapted and incorporated into a recommended plan that can be incorporated into town planning and incrementally implemented over the ensuing decades as the threat to Cairns increases and costs allow.

It is anticipated that the draft dissertation will be due for formative assessment around 8 September 2022 and the completed dissertation around 13 October 2022. The schedule may need adjusted there are unanticipated delays or critical dates change. The anticipated schedule to complete each phase is shown in the table on the next page.

Table 1: Project schedule

Task	Semester 1														
					MID SEM. BREAK									EXAMS	
	7-Mar	14-Mar	21-Mar	28-Mar	4-Apr	11-Apr	18-Apr	25-Apr	2-May	9-May	16-May	23-May	30-May	6-Jun	13-Jun
Supervisor Meetings			23-Apr		6-Apr		20-Apr		4-May		18-May				
Phase 1: Project preparation															
1A: Cairns background information															
1B: World wide flood mitigation strategies															
1C: Comprehensive list of realistic options															
Phase 2: Permanent Sea Wall Analytical Hierarchical Process															
2A: Determine evaluation categories and weighting															
2B: Category justification															
2C: Initial analysis and option ranking															
2D: Identify top Solution															
Phase 3: Modular Sea Wall AHP & Combined Designs															
3A: Repeat Phase 2 with modular retaining wall designs															
3B: Analyse different combined sea wall designs															
3C: Identify best combined design															
3D: Recommended solution/plan															
Phase 4: If time permits															
4A: Alternative options															
4B: Incorperation of other nearby locations															
4C: Drainage recommendations															

Task				Semester 2																
	BREAK													MID SEM. BREAK					EXAM	
	20-Jun	27-Jun	4-Jul	11-Jul	18-Jul	25-Jul	1-Aug	8-Aug	Aug	22-Aug	29-Aug	5-Sep	12-Sep	Sep	26-Sep	3-Oct	10-Oct	Oct	Oct	Oct
Supervisor Meetings				13-Jul		27-Jul		10-Aug		24-Aug		7-Sep				5-Oct				
Phase 1: Project preparation										**Key dates**										
1A: Cairns background information										Fortnightly meeting with supervisor										
1B: World wide flood mitigation strategies																				
1C: Comprehensive list of realistic options																				
Phase 2: Permanent Sea Wall Analytical Hierarchical Process																				
2A: Determine evaluation categories and weighting																				
2B: Category justification																				
2C: Initial analysis and option ranking																				
2D: Identify top Solution																				
Phase 3: Modular Sea Wall AHP & Combined Designs																				
3A: Repeat Phase 2 with modular retaining wall designs																				
3B: Analyse different combined sea wall designs																				
3C: Identify best combined design																				
3D: Recommended solution/plan																				
Phase 4: If time permits																				
4A: Alternative options																				
4B: Incorperation of other nearby locations																				
4C: Drainage recommendations																				

Appendix G – Quality assurance and risk management plan

To ensure the findings and recommendations of this research project are realistic, practical and of sufficient quality they will be assessed against the following criteria:

- Is the solution feasible – can it be done?
- Is it economically viable? If the solution is not cost effective/affordable then it is not a realistic solution.
- Will the solution be socially acceptable? Does it fit in with Cairns as an international tourist destination; ascetically acceptable, relatively unobtrusive?

In addition, the report will be completed to the standards set by the University of Southern Queensland whilst also emulating the standard set in the Cairns Coastal Hazard Adaption Strategy (CHAS) document that forms the basis for the project. Regular feedback will be sought from the project supervisor to ensure a high standard is maintained and project outcomes remain achievable.

G1.1 Risk assessment

No ethical, legislative, environmental, financial or public safety risks were identified. Therefore, In the context of this research project, risk means the probability of something happening that results in injury whilst the project is being undertaken or something negatively impacting the ability for the project to be completed. A risk assessment of the activities associated with the project is shown in a risk assessment table with the rating determined by the likelihood of the event against the severity of the consequence as identified in the risk assessment matrix.

The risk of personal injury whilst undertaking the project is low. However, it should be noted that the risk to the project from illness or injury occurring near the end of the project has a high probability of negatively impacting completion of the project. There are numerous other risks that also have a high probability of negatively impacting the project. These mainly relate to the uncertainty of having the project approved in its current form, the uncertainty of what the research project will identify and how this may be applied to Cairns and ability to complete the project in the given timeframe.

Table 1: Risk assessment matrix

Likelihood	Consequence				
	Insignificant	Minor	Moderate	Serious	Very serious
Almost certain Greater than 90% chance	Medium	High	High	Extreme	Extreme
Likely Between 50% and 90% chance	Medium	Medium	High	High	Extreme
Moderate Between 10% and 50% chance	Low	Medium	Medium	High	High
Unlikely Between 3% and 10% chance	Low	Low	Medium	Medium	High
Rare Less than 3% chance	Low	Low	Low	Medium	Medium

Table 2: Project risk assessment

Risk/Hazard	Risk rating	Risk mitigation measures
Phase 1: Project preparation		
Preliminary approval not given.	**Medium**	Complete a quality, in-depth and convincing research proposal.
Final project approval not given.	**High**	Complete a quality, in-depth and convincing research proposal.
Project significantly changed.	**High**	Complete a quality, in-depth and convincing research proposal that is achievable and fully meets expectations for a fourth-year dissertation research project.
Cairns Regional Council release further plans that mirror the scope of this project and fill the gap in knowledge.	**High**	Cairns Regional Council progress in developing solutions to inundation threats is not known. There are no mitigation strategies other than to change the project parameters to work around council solutions - look for further gaps or areas of difference in solutions.
Unable to undertake initial field study.	**Low**	Initial assessments can be completed from memory of locations and satellite images if necessary. Could rely on the semester break field study only.
Research takes longer than anticipated.	**Medium**	Plan ahead, start early and keep to the project schedule.
Online inundation maps become unavailable.	**Medium**	Save copies to my computer.
Illness near start or mid project.	**Low**	No realistic mitigation measures, look after health.

Phase 2: General Analysis		
Research fails to identify sufficient solutions.	**High**	Further research - seek assistance from librarian and advice from project supervisor.
Solutions cannot be adapted to the Cairns locality.	**High**	Research further to obtain further ideas and solutions. Seek advice from project supervisor.
Solutions are not affordable.	**Medium**	Research further and find other solutions.
Phase 3: Detailed Analysis of top five solutions and development of recommendations		
Research fails to identify sufficient solutions.	**High**	Further research - seek assistance from librarian and advice from project supervisor.
Solutions cannot be adapted to the Cairns locality.	**High**	Research further to obtain further ideas and solutions. Seek advice from project supervisor
Solutions are not affordable.	**Medium**	Research further and find other solutions.
Recommendations and plan are not accepted/implemented	**High**	Consultation with key parties, further research and modifications to obtain acceptable plan.
Field work		
Over exposure to sun whilst completing field work.	**Medium**	Wear protective equipment (hat, sunscreen), sufficient water, early morning or late afternoon, avoid fieldwork during mid-day sun.
Injury whilst completing field work (falls, car accident).	**Low**	Be aware of surroundings, sensible and responsible behaviour.
Route for seawall cannot be found.	**High**	If no realistic and affordable route can be found, substitute and ideal route as if existing infrastructure and affordability were not constraints.
Report write-up		
Repetitive strain injuries from extended computer use (eye strain, back issues, blood constriction).	**Low**	Set computer up properly in well lit, cool areas. Correct posture. Take a break every hour, short walk to exercise muscles.
Loss of research data and records.	**High**	Regularly back up data.
Illness near end of project prevents completion	**High**	Look after health, aim to be ahead of project schedule.
Insufficient time to complete all phases of the project.	**High**	Be prepared to drop the water catchment phase of the project.
Insufficient time to complete write-up.	**High**	Complete draft write-up as each phase completed rather than leaving to the end.
Non-acceptance of project findings and recommendations.	**Medium**	Adhere to Quality Assurance Plan and focus on quality realistic/achievable outcomes.