A National Study on Protecting Australian Infrastructure and Public Buildings Against Sea Level Rise and Storm Surge

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Executive Summary

Sea Level Rise (SLR) and minimal storm surge is a $106 billion threat to Australia by 2040 that includes a need for at least 12,000 kilometers of protective barriers. This threat extends across every Australian state. The threat includes large cities such as Sydney and Perth together with small local government areas such as Burke, QSD and Queenscliffe, VIC. The threat exists for every coastal community, regardless of size, population, or financial position.

The current study developed these results based on 36 different SLR and storm surge scenarios across 4.1 million geographic locations and 3 time periods. Taking an approach based on engineering design guidelines and current cost estimates, the study details projected cost impacts for states, state electoral districts, and local government areas. These impacts are presented from the perspectives of both total cost and cost per-capita.

The identification of SLR threats places a spotlight on the potential issues associated with addressing this threat. Specifically, four challenges are identified; 1) the realization that the response timeline is possibly shorter than many communities have considered, 2) the tension between urban and rural communities in terms of which communities might get priority for limited protection resources, 3) the feasibility of constructing a minimum of 12,000 kilometers of sea wall prior to 2040, and 4) the challenge of protecting infrastructure versus relocating and rebuilding.

In summary, SLR and storm surge present a new set of natural hazard risks to public officials and planning officials. The current study does not engage in the scientific discussion of whether SLR will happen, or to what degree the science accurately projects the SLR risk. Rather, this study introduces SLR as a risk that must be incorporated in planning by public officials in all coastal communities. Most importantly, the study highlights the need to fund a national SLR protection effort.

SLR requires that public officials overcome local perspectives to focus on collaboration. Priorities will need to be set to determine how and when communities receive assistance in implementing a protection plan. The question of how to develop this prioritization is one with no easy solution. However, public officials have a choice; focus on the differences between the communities (size, population, total risk), or focus on possible solutions that can be mutually beneficial. The choice that is made will set the stage for the future of many communities.

Two decades will pass quickly when put in the context of constructing a national network of protection for SLR. With a conservative cost of $106 billion and a projected length of over 12,000 kilometers, decision makers are facing a challenge to either start planning for construction or find a viable alternative that meets both local and national requirements.

Introduction

Climate change presents a wide range of challenges for infrastructure owners, planners, and users. Transportation networks are threatened both at the individual component level such as roads being washed away by increased flooding, and at the overall system level where vital connection points such as ports and airports are threatened by sea level rise and increased temperatures (Jacobs et al 2018). However, the impacts of climate change are not limited to a single category. Physical assets including buildings, power generation facilities, and bridges are a few of the infrastructure categories that face challenges from a changing climate. Economic concerns are also threatened with projections of business interruption, supply chain disruption, and logistics challenges creating concern among business owners (Clarke et al 2018). And public health concerns continue to emerge as issues from vector borne diseases to asthma are being studied in terms of climate change impacts (Ebi et al 2018).

Of the broad range of potential impacts from climate change, the impact that is predicated to have the potentially largest impact in Australia is Sea Level Rise (SLR). SLR is a widely agreed-upon consequence of climate change and it is established across the field of climate change research that if a rising temperature continues to manifest on a global scale, sea level rise will occur due to a combination of thermal expansion of sea water as it warms and the melting of land-based ice into the ocean (Nicholls 2011). The consequences of this sea level rise on coastal road networks, buildings and infrastructure due to economic, social and environmental costs are predicted to be substantial (Melillo et al. 2014), (Jacobs et al. 2018). These costs are a burden not only to the government in terms of maintaining and repairing damaged infrastructure, but they can put the lives and livelihoods of individuals in peril.

According to Geoscience Australia, the total Australian coastline is 59,681 kilometers in length[1]. In an initial national study by the Australian Department of Climate Change, around 85% of the Australian population lives in the coastal zone (Dept. of Climate Change 2009).

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[1] www.ga.gov.au/scientific-topics/national-location-information/dimensions/border-lengths

As detailed in the report, estimates for the projected sea level rise for this area ranges from 75 centimeters to 190 centimeters with a mid-range of 110-120 centimeters. This projection puts between 157,000 and 247,000 buildings at risk as well as almost 2,000 bridges.

Because coastal areas are attractive areas to establish thriving communities, both economically and physically, the expected and predicted SLR leaves many systems along the coast vulnerable to damage, resulting in severe economic consequences. Between 26,000-33,000 kilometers of roads are at risk from inundation as well as 1,200 to 1,500 kilometers of rail lines (Ware 2016).

The size and extent of this threat is bringing to the forefront of policy discussions the question of what should be done to protect coastal communities from the threat of sea level rise as well as the increasing threat from coastal storm surge. This discussion crosses the political, economic, and engineering domains as the question emerges as to the appropriate approach that should be taken in response to the threats (Neumann et al 2015; Butler et al 2016; Yusuf et al 2016; Merrill et al 2018).

Specifically, the question of whether SLR vulnerability requires new policies to relocate communities, or new investments to construct protection barriers, or whether communities should take a wait-and-see approach is one that can no longer be delayed. Actionable plans need to be developed by coastal communities throughout Australia to effectively direct political discussions on appropriate responses for individual communities. The foundation of these discussions must revolve around a common factor that all parties can reference when staking out SLR positions.

Currently, the approaches to SLR response can be divided into three broad categories; protection, accommodation, and retreating. The protection category includes creating dikes, surge barriers, closure dams, constructing dunes, nourishment and sediment management of wetlands, creating coast defenses, sea walls and land claims, creating saltwater intrusion barriers and implementing drainage systems/polders. The accommodation category includes implementing building codes to minimize the flooding of critical building spaces, ensuring land use planning that accommodates for wetland loss, changing water extraction practices, using freshwater injections to stop saltwater intrusions and increasing the delineation of natural hazard areas. Finally, practices that pertain to retreating focus heavily on policies that minimize new building in areas where SLR threatens infrastructure, as well as considering the movement of existing structures in threatened areas (Nicholls 2011).

While protection, accommodation, and retreat present a large array of approaches to protecting against SLR, historically, the implementation of sea walls, also known as rock revetments or armoring, has been the most common approach to reducing the impact of sea level rise on coastal communities (Sutton-Grier et al 2015; Griggs 2005). Coastal armoring, or building of sea walls, has been used to protect eroding or wave-impacted coastlines and have additionally been used to stop or reduce the impacts of flooding. Similarly, the building of inland sea walls, also known as bulkheads, along the banks of inland waterways have been the predominant approach to protecting property against rising waterway levels. While these are the predominant approaches to protecting coastal properties, seawalls do not work in every circumstance. Specifically, in cases where porous materials such as limestone form the bed of the waterway, water can infiltrate through the rock and under the seawall. In these cases, alternatives including the addition of pumping may be necessary.

Based on the historic focus on sea walls as a protection strategy, the current study addresses the foundational question of, “What is the cost to protect coastal areas that are projected to be impacted by SLR as well as increases in storm surge flooding?”

This study provides a national estimate of the construction costs associated with armoring areas of the coast that are projected to be flooded and which contain built assets. These assets include both public and private assets such as roads, rails, and public buildings. Private residences are not specifically modelled in this effort. However, residences are included indirectly by protecting the locations that include roads and other public infrastructure elements that support these properties.

The intent of the current study is to provide the best estimate of expenses that have the highest likelihood of being incurred over the next 5-10 years. The study utilizes inundation projections from the lower bounds of those published to ensure that the overall results provide an indication of hard costs that are likely to be incurred by local, regional, and national entities.

The cost estimates presented here are considered conservative in that they are estimated construction costs that may increase due to specific conditions in local areas. The costs also do not include long-term maintenance costs or the potential for cost increases due to inflationary pressures. Thus, the actual costs incurred by municipalities is likely to be higher than the costs presented in this study.

Overview of Sea Level Rise Impact Modeling

A variety of approaches have been used to model and estimate the potential economic, social and environmental costs created by sea level rise. These procedures vary in methodology used, geography assessed, and scale implemented. As related to the current study, these studies can be grouped into three general categories: vulnerability studies, economic studies, and adaptation studies.

Vulnerability Studies

The first group of studies emphasizes the use of models to predict and model the vulnerability of coastal infrastructure. Vulnerability models utilize climate models combined with Geographic Information Systems (GIS) and Digital Elevation Models (DEM) to predict populations and infrastructure at risk. These models are often based on what is referred to as a bathtub representation that gives an estimate of when water basins will flood due to increased water volume (Williams and Luck-Vogel 2020). Barankin et al (2020) is an example of focusing on a small, but detailed geographic area to provide vulnerability estimates based on local conditions. The study focuses on transportation systems in Massachusetts to identify specific locations where adaptation priorities should be emphasized. The study focuses on determining critical infrastructure assets, but it does not provide cost information for adapting these assets. Habel et al (2020) also emphasize the identification of critical assets as they focus on infrastructure in Hawaii to identify the multiple modes in which flooding may impact local infrastructure. This research highlights the direct and indirect flooding that is projected from SLR and its effects on both coastal and inland infrastructure.

Expanding on the base flooding vulnerability, Neumann at el. incorporate “a tropical cyclone simulation model, a storm surge model and a model for economic impact and adaptation” to estimate the impacts of sea level rise for the US coastline through 2100 (Neumann et al 2014; Neumann et al 2011). The model integrates site-specific elevation, land subsidence and property value data to estimate the costs incurred due to shoreline armoring, beach nourishment and property abandonment. Similarly, Khanam et al (2020) address the challenge of combined flooding hazards in coastal river areas to illustrate how independent factors do not fully project vulnerabilities introduced by a significant weather event. Additionally, the 100-year flood maps may be insufficient to address emerging flood risks.

Economic Studies

The second category of studies focus on projecting the social and economic impacts of SLR and annual flooding on coastal communities and economies. Hsiang et al. (2017) utilize SEAGLAS (Spatial Empirical Adaptive Global-to-Local Assessment System) to estimate the cost of climate change to the sectors of agriculture, crime, coastal storms, energy, human mortality and labor using a "risk-based approach" which is "grounded in empirical longitudinal analyses of nonlinear, sector-specific impacts". The results suggest that climate change costs approximately 1.2% of the gross domestic product per +1°C. Similarly addressing economics, Fu and Wijman (2020) utilize a comparative approach to determine the effect of SLR on home values in South Florida. This approach utilizes comparisons between similar cities, both in respect to location and home values, but differ in term of emerging flooding exposure. The study found that properties below 3 feet in elevation are experiencing a value impact. As with studies by Walsh et al (2019) and Murfin and Spiegel (2019), these comparative studies are providing evidence that increased exposure as well as adaptation decisions are having a direct impact on current and projected home values.

Adaptation Studies

The final area of studies that influence the current work is the area of adaptation studies. These efforts extend beyond the vulnerability of infrastructure and the economic impacts to address the potential costs and options for adaptation. These studies can be system specific such as in transportation or water treatment, or broad to address community-wide adaptation strategies. Of these, system specific studies have been the predominant focus over the last decade. Mattsson and Jenelius (2015) approach the topic through a review of transportation studies emphasizing network interruption. Similarly, Kim et al (2018) approach resiliency and adaptation based on an overview of strategies developed in response to major events such as Superstorm Sandy. In each of these studies as with similar ones, the focus is on options to protect specific systems in response to anticipated increases in weather events.

In contrast to these single-system studies, community-wide or multi-system studies focus on the need to address multiple infrastructure threats to ensure resiliency. Shakou et al (2019) adopt this approach with an emphasis of criticality identification in infrastructure systems. Zuniga-Teran et al (2020) emphasize a green infrastructure approach to the resiliency of multiple infrastructure systems. Finally, Kong and Simonovic (2019) take a probabilistic approach to reviewing current adaptation approaches and presenting a multi-hazard resilience strategy. These studies represent the types of approaches being used to address the complex implementation of adaptation strategies.

While the adaptation studies provide key insights into the challenges of adaptation planning and adoption, the studies leave a gap in terms of understanding the total financial impact of SLR. This gap, along with the need for a national geographic focus, is the motivation for undertaking the current study in the context of the Australian coastline.

Methodology

The estimation of the potential cost of protecting the coastline from the impacts of SLR and storm surge entailed a multi-step process incorporating climate projections, geoprocessing of detailed coastline flooding maps, the computational assessment of where coastline needed protection, and the calculation of the costs associated with this protection. The process developed for this estimation is based on previous climate impact work developed by Resilient Analytics for infrastructure impacts locally, regionally, and globally (Cervigni et al 2016; Chinowsky et al 2017; Schweikert et al 2018).

The following sections provide an overview of the process used to develop the estimates presented in this report. Each section is an introduction to the methods developed specifically for this analysis. The methodology is intended to be reproducible to allow for further analysis at local scales.

Geoprocessing

The first step in the impact process was the identification of areas where inundation and flooding were projected along the coastline and inland waterways (Figure 1). The study utilized SLR and 1-year storm surge inundation projections from CLIMsystems, Ltd for this identification effort. The high-resolution data sets for the Australian coast are based on published sea level rise projections as well as research conducted by CLIMsystems (Kopp et al 2017; Kulp and Strauss 2016; Tebaldi et al 2012). The data sets provided projection data for all areas that may be impacted by permanent SLR or permanent SLR coupled with 1-year storm surge events. The data set is built from a 90-meter x 90-meter digital elevation model (DEM) to ensure accurate capture of tidal inlets.

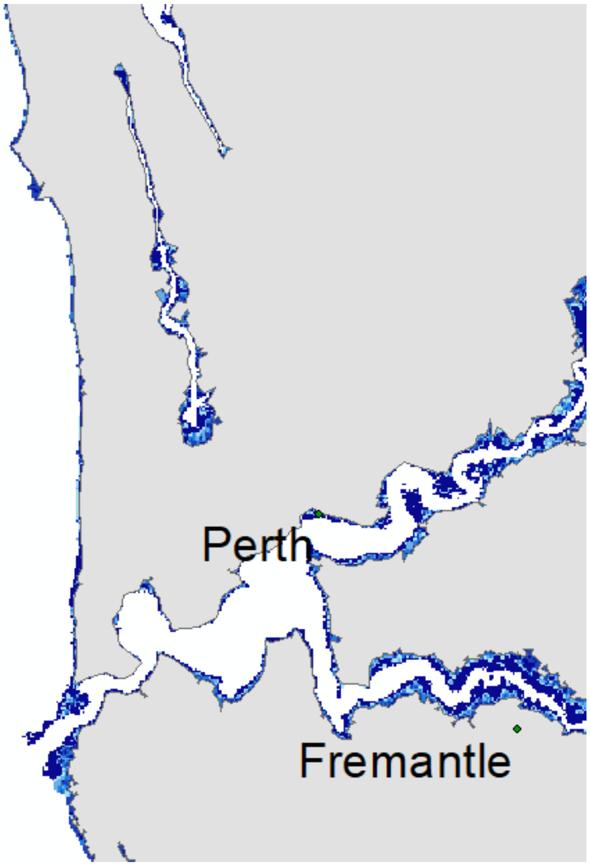

Figure 1: Example of base inundation map used to determine the flooding areas within each geographic area. Shaded areas indicate flooding from this scenario.

As stated previously, the focus of the current study is to provide the best estimate of expenses that have the highest likelihood of being incurred in the next 5-10 years. From this perspective, the study includes two conservative but likely RCP pathways, RCP 4.5 and RCP 6.0, to provide the best estimate of expenses that have the highest likelihood of being incurred. The inundation data sets provided for the study were derived from a set of projections generated by CLIMsystems. Specifically, the 5th, 50th, and 95th percentile inundation projections for each of the two pathways from the overall dataset were selected for the current study. Three time periods were selected from the results for the impact analysis; 2040, 2060, and 2100. Additionally, the inundation data was included with and without 1-year storm surge projections to capture both the base SLR impact and the potential for regular flood impacts. These combinations resulted in a total of 36 different scenarios for use in the study.

In order to understand the impact that the projected flooding will have on public infrastructure, it was necessary to determine the location of infrastructure in the impacted areas. Resilient Analytics accessed publicly available GIS files of Australian infrastructure locations from Geoscience Australia[2] to determine specific areas requiring protection (Figure 2). A complete national building stock was unavailable, so the areas of Australia that contain public buildings including schools, hospitals, medical facilities, and government buildings were estimated using the "built up areas" variable from Geoscience Australia. A complete set of public horizontal infrastructure (roads, railways and runways) was available. Although the study does not consider private residences directly, the location of most residential areas can be determined through the location of public roads that are used to access residential areas. Therefore, by considering all areas that contain a road (both paved and unpaved), the majority of residential areas were also considered. Areas that do not have any public infrastructure, such as national parks or protected wildlife areas, were not included in the study.

Once the inundation and the infrastructure datasets were obtained, the second step in the process required placing these results in a gridded system that could support spatial analysis. Specifically, a transformation of the data was required to reduce the datasets to an indication of whether infrastructure was in a specific area and whether that area was projected to be impacted by SLR or storm surge. This transformation was executed using built-in geoprocessing tools within ArcGIS. Although the original climate data was provided at an ultra-high resolution, for processing speed, usability and accuracy, the data was condensed to a uniform grid size. Sensitivity analysis tests were performed to determine an appropriate grid size that would allow for the most accuracy in results while still maintaining computability speed. The sensitivity analysis focused on determining the largest grid size that would both retain the underlying inundation detail as well as accurate location information for the infrastructure being analyzed. Through a series of test runs of increasing grid sizes, the sensitivity analysis found that a grid system of 150 m^2 would achieve the study objectives (Figure 3).

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[2] GIS maps accessed online at https://www.ga.gov.au/data-pubs

The result of the transformation process was a database that included the infrastructure location and the predicted inundation for each climate scenario at a resolution of 150m x 150m.

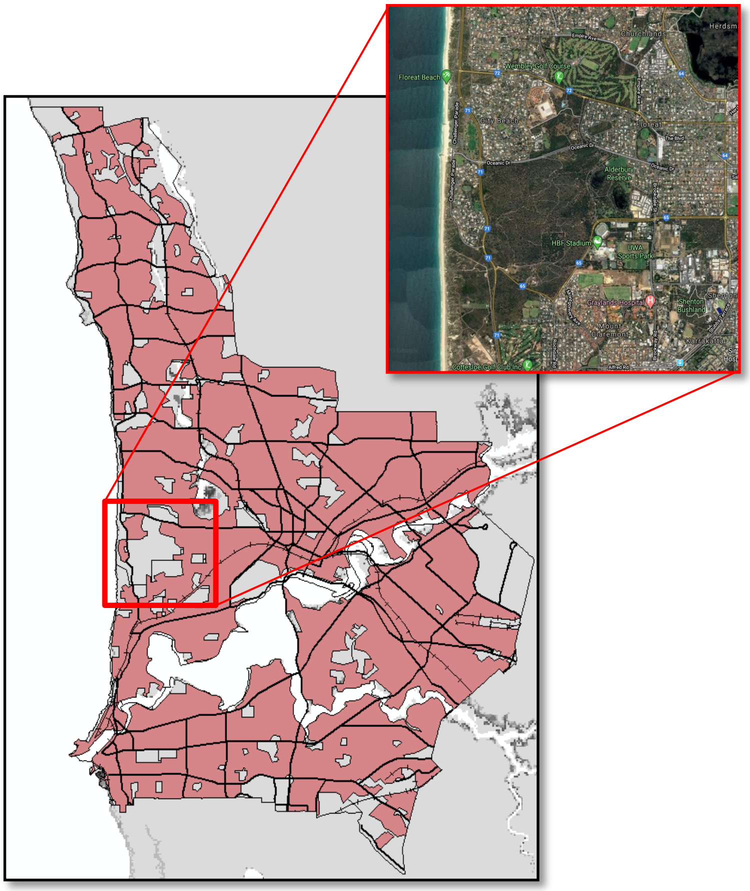


Figure 2: Flooding areas combined with infrastructure to be protected. Areas where infrastructure intersects with flooding are considered vulnerable and require protection.

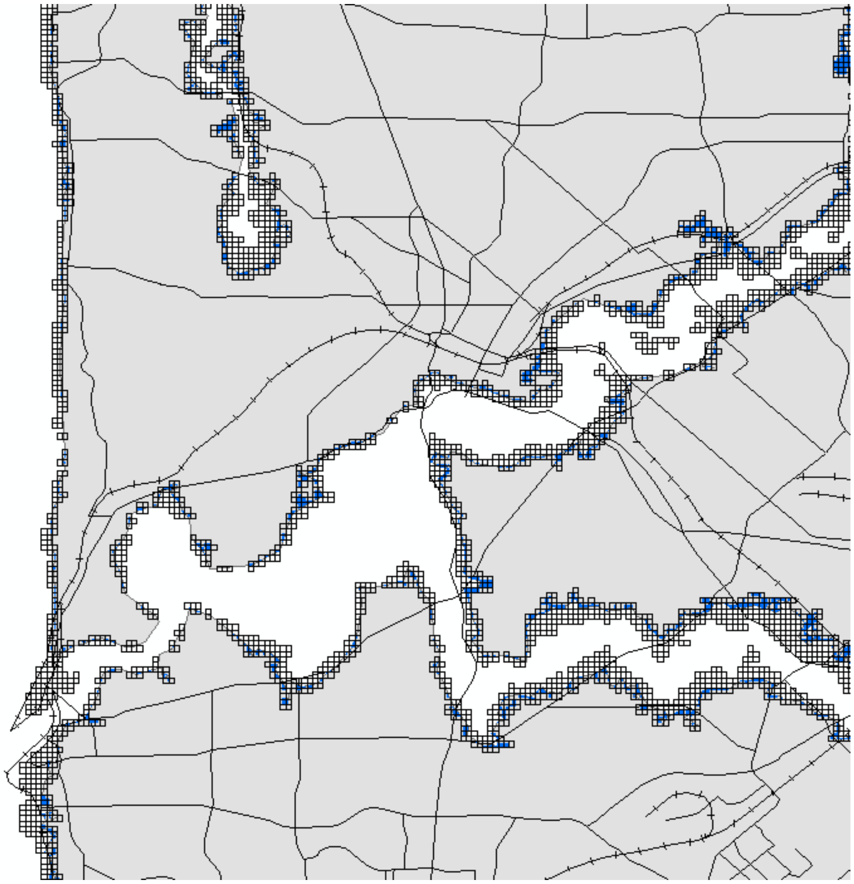
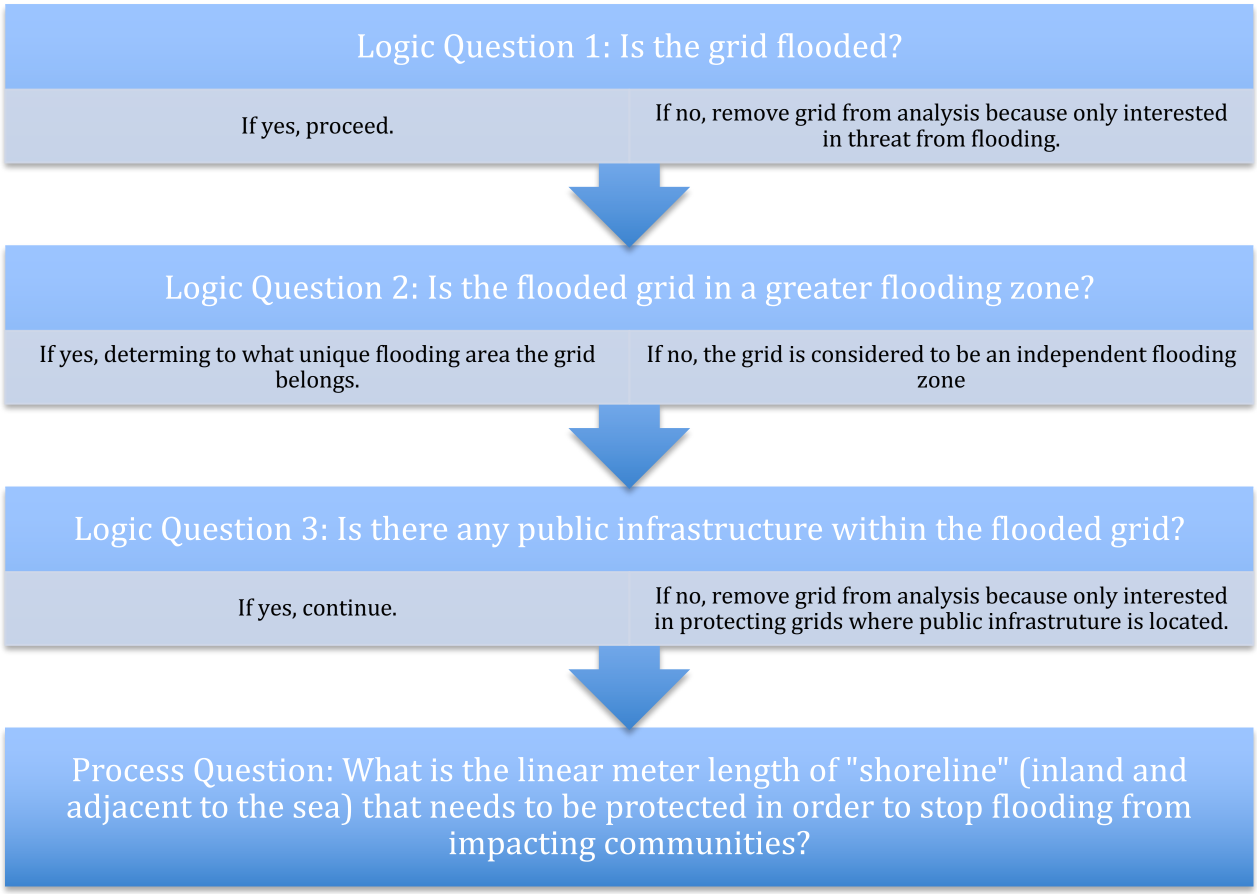


Figure 3: The 150^2m grid overlayed on the infrastructure and inundation zones. Each grid contains the information on the projected flooding and the infrastructure to determine length of protection required for each grid.

Protection Assessment

Once the flooding files were processed, the second step of the process required determining what areas of coastline needed protection to remove the threat of flooding. This determination requires a series of logic tests to understand if a flooded grid is directly impacted by flooding from adjacent waterways, or if it is indirectly affected by other grids that are adjacent to waterways. The overall logic process for the protection assessment is illustrated below.



Logic Question 1: Is the grid flooded?

If yes, proceed.

If no, remove grid from analysis because only interested in threat from flooding.

Logic Question 2: Is the flooded grid in a greater flooding zone?

If yes, determing to what unique flooding area the grid belongs.

If no, the grid is considered to be an independent flooding zone

Logic Question 3: Is there any public infrastructure within the flooded grid?

If yes, continue.

If no, remove grid from analysis because only interested in protecting grids where public infrastruture is located.

Process Question: What is the linear meter length of "shoreline" (inland and adjacent to the sea) that needs to be protected in order to stop flooding from impacting communities?

The first logic question determines if any given gridded square is located within an area that is expected to flood, according to a specific climate scenario. This question is nuanced in that there must be a determination as to how much of a grid cell needs to be flooded for it to be considered a flooded grid. The need for this determination originates from the issue of how to limit the protection of coastal grids that appear in the study with minimal flooding along the edge of the coastline. For example, a grid covering an inlet which is indicated to have inundation over an area covering just a few yards onshore, and does not include flooding of any infrastructure, can be eliminated in terms of needing protection. The 15% flooding variable assists in eliminating these overprotection scenarios. The value of 15% was chosen based on engineering judgement upon inspection of protection patterns using 5%, 10%, 15% and 20%.

The second question focuses on whether a grid is flooded due to direct flooding or indirect flooding. The model works from the assumption that wherever flooding occurs, the shoreline directly impacting that flooded area needs to be protected. The case of direct flooding occurs when a grid is adjacent to a waterway and the scenario indicates that grid is flooded due to the overtopping of the adjacent waterway. In this case, the adjacent shoreline needs to be protected to prevent the grids from incurring flooding. The indirect case occurs when an inland grid is flooded due to being connected directly or indirectly to a water-facing grid. In this case, the model must trace the path of the flood back to its origin which is the grid adjacent to the coastline. The model then protects the coastline adjacent grid to eliminate the threat to the overall flood area.

Once the full set of flood areas is determined and the areas of flood origination are identified, the third step of the process is initiated. In this step, the model determines what portion of the identified flood area needs to be protected based on the presence of infrastructure. This step is required to ensure that areas without infrastructure are not unnecessarily included in protection costs. This eliminates the need for protection in areas such as nature preserves or remote areas that are uninhabited. A policy decision may be made at a future date that these areas should also be protected, but that would increase the overall projected costs for protection.

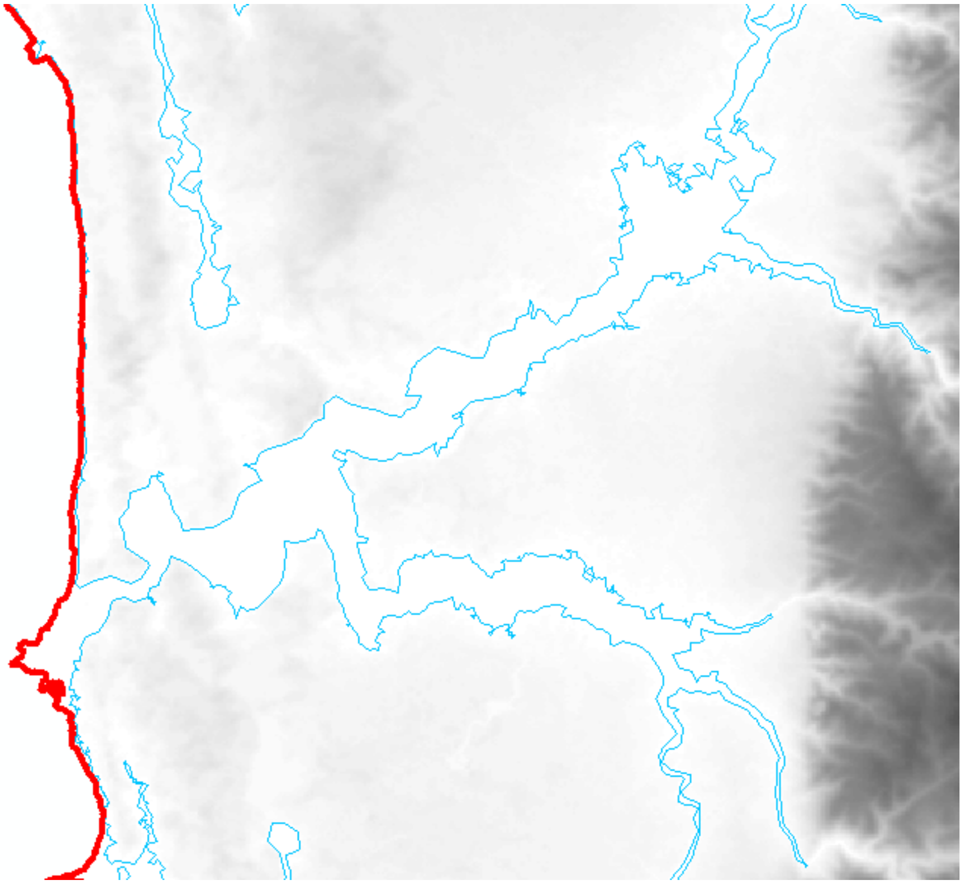


Figure 4: Illustration of the coastline derived from the DEM sources compared to low resolution coastal boundaries. The dark line indicates low resolution coastline calculations in comparison to the multiple inlets that are the true length of coastline.

The identification of the flood areas provides the entry point for the final step in the process of calculating the length of coastline to be protected. The current study utilizes the Geoscience Australia 5-meter DEM, resampled to 90 m and the HydroSHEDS 90m Conditioned DEM to determine what is considered shoreline (Figure 4). This data was selected to ensure that the coastline was consistent with the original data provided by CLIMsystems based on the same DEM sources. As illustrated in the map of the greater Perth area in Figure 5, the DEM sources provide detailed imaging of the inlets and tidal areas within that geographic location. This is in contrast to lower resolution maps which simplify the coastline as indicated by the red line that eliminates the inland portions of the coastline. The result of using this higher resolution map is that the actual length of coastline increases, in some cases significantly, as the true length of coastline can be calculated. In the current study this translates to a study length of approximately 130,000 km in comparison to the Geoscience Australia measurement of approximately 60,000 km. An even greater level of detail is possible through the use of high-resolution maps however these are not available at a national level at this time. The use of these maps may in fact increase the projected costs as greater lengths of coastline may be detected.

Because the study is interested in understanding what the cost to protect infrastructure using shoreline armoring or sea wall, determining the length of coastline as accurately as possible within the constraints of the study was critical. After completing the protection length calculation, the model analyzed the coastline for every grid that was determined to have a flooding impact on identified infrastructure. For each of the identified grids, the length of coastline in that grid was calculated to a linear meter.

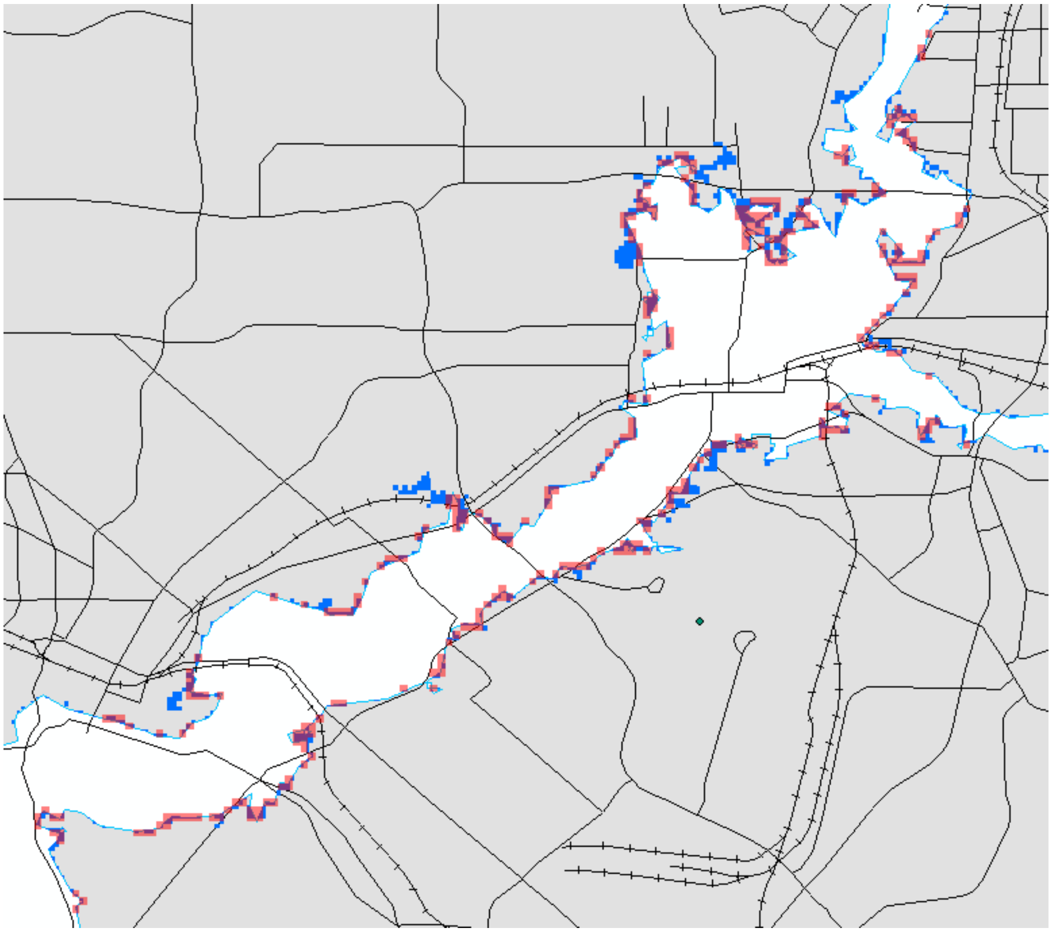


Figure 5: The 150^{2}m grid overlayed on the horizontal infrastructure and inundation zones (dark blue) combined with the projected protection zones. Each red grid indicates an area requiring protection. The light blue lines indicate shoreline.

Costing

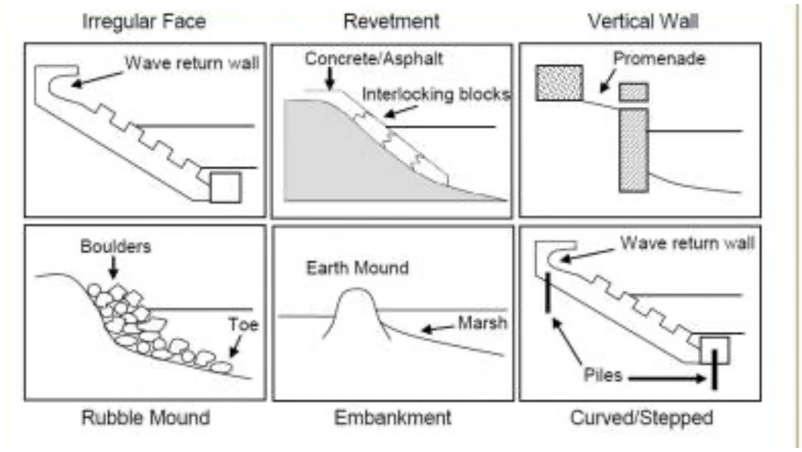


Figure 6: Typical revetment designs for coastal facing seawalls.

The calculation of the linear length of coastal protection that was estimated to offset the impact of SLR and storm surge provided the input to the last step in the process, determining the overall cost. Costing assessments were created using a combination of national cost databases and local estimates from seawall design and construction companies to establish localized, realistic per-kilometer costs.

The cost estimates are divided into two categories, coastal seawalls and inland seawalls. In terms of the former, coastal seawalls are comprised of armored revetments that are either adjacent to shore structures or serve as standalone offshore structures. Figure 6 illustrates various design alternatives for creating seawalls[3]. The current study utilizes a typical design approach of using field stone to create an armored revetment on the shoreline. This design is utilized in the model wherever the coast exposure is direct to open water.

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[3] Figure accessible at https://www.climatetechwiki.org/content/seawalls

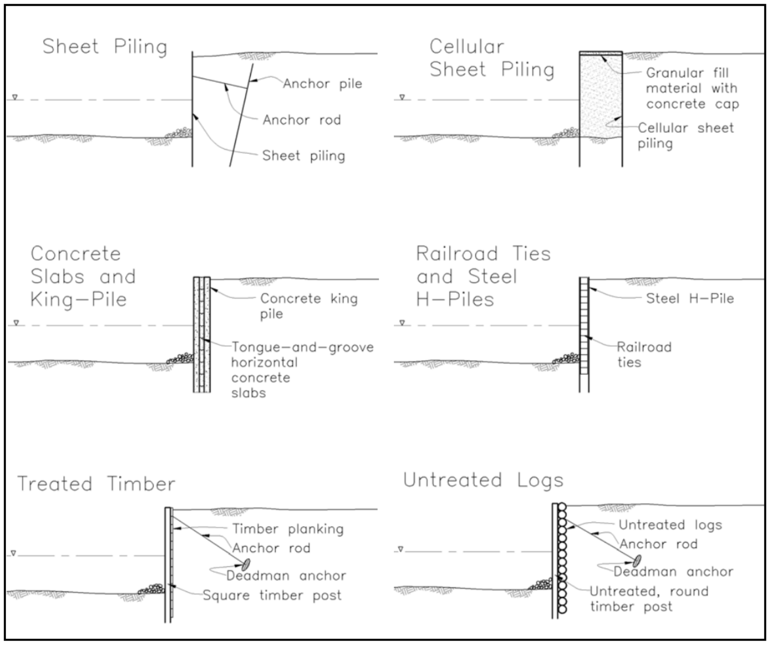

Figure 7: Typical bulkhead seawall designs for inland waterways.

Figure 7 illustrates design options for inland seawalls, often referred to as bulkheads[4]. These designs focus on protection of shoreline from the increased water level as well as from indirect wave action. Bulkheads are generally constructed of steel sheet piling, wood, or concrete where more permanent protection is required. The primary cost factor in these solutions is the installation which may vary depending on where the bulkhead is located. However, this is a proven technology with applications in many geographic locations.

Once the model determines whether a revetment-based design or a bulkhead-based design is appropriate for the given grid location, the cost of that solution is multiplied by the linear length of protection required to obtain a total cost that is reflective of the location and type of protection required.

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[4] Available at https://www.essie.ufl.edu/~slinn/structures/14%20Design%20of%20Sheet-Pile%20Walls%20&%20Bulkheads.pdf

Cost Allocations

The protection costs in the next section are presented in different geographic and logical breakdowns. To achieve these multiple perspectives, the modeling system leverages the grid system allocation that underlies the overall analysis. Through available GIS map overlays, state, local government area, and state electoral district boundaries were placed on the underlying grid-based results. Through this overlay process, multiple perspectives on total protection costs have been extracted from the model. The process can be extended for any geographic or logical boundaries that are required from the underlying dataset.

Results

The protection of the coastline across seven states is a significant task that will require the cooperation of national, regional, and local entities. As illustrated in Figure 8, a mid-level climate scenario in 2040 projects that every coastal-facing state is threatened by sea level rise and storm surge at a national cost conservatively placed at $106 billion. This exposure elevates the SLR issue from a local problem that places the burden on local officials to a national issue that requires collaboration at all levels. In this section, the results of the SLR study are presented at the national, state, and local governmental area levels to emphasize the multi-jurisdictional impact of SLR and the need to elevate the issue to a national conversation.

As detailed in the methodology section, the current study analyzed 36 different climate scenarios to determine the potential impacts of SLR and storm surge. The 50th percentile of the RCP 4.5 scenario at 2040 is highlighted in the following sections. The results reflect the

NATIONAL MAP

2040 Costs, RCP 4.5, 50th Percentile model results, AUD Billions

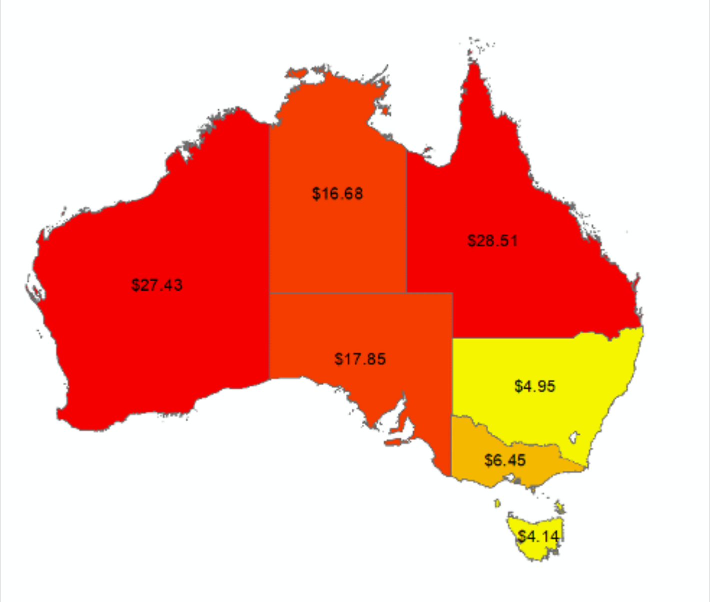

Figure 8: The 2040 SLR projection with storm surge indicates that every coastal-facing state will incur costs to a conservative aggregate total of $106 AUD billion.

SLR and 1-year storm surge projections. The combination is presented as construction of protection barriers would reasonably be completed with the consideration of the persistent flooding.

National/State Results

The construction cost to protect coastal infrastructure from SLR and storm surge is conservatively placed at $106 AUD billion in 2019 dollars when considering a projection using the 50th percentile estimate of RCP 4.5. This estimate grows to $131 AUD billion in 2019 dollars when the same scenario is extended to 2100 (Figure 9; Tables 1 and 2). This number does not include maintenance costs, future replacement costs, or potential inflationary pressures due to a limitation of material or personnel resources.

NATIONAL MAP

2100 Costs, RCP 4.5, 50th Percentile model results, AUD Billions

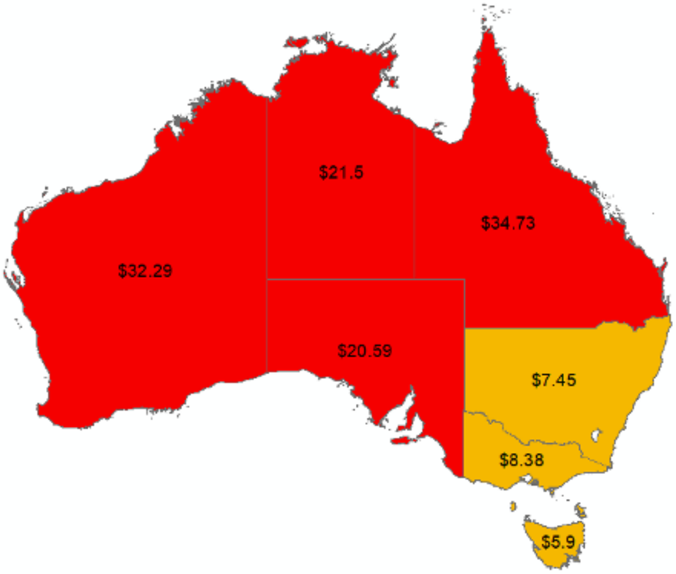

Figure 9: The 2100 SLR projection with storm surge increases the potential cost of protection for coastal assets to $131 billion based on the mid-range projection.

Regionally, the western and northern states (Western Australia, Northern Territory, and Queensland) see a combined impact of $88.5 billion by 2040 with Queensland having the largest impact with a potential impact of $34.7 billion. While these regions are often seen as less impacted due to smaller populations, the intricate coastlines require significantly more kilometers of protection for infrastructure. However, as will be discussed later, the population versus infrastructure ratio makes decision making regarding protection versus realignment of infrastructure a more difficult question.

South Australia sees an impact of $20.6 billion by 2040. This area is significantly impacted by the shoreline associate with St. Vincent Gulf and Spencer Gulf combined with the population center of Adelaide. The challenge for South Australia lies in the fact that a significant percentage of its almost 100,000 kilometers of roads are exposed to sea level rise as they are located within coastal areas. Notably the roads in the southeast corner of the state which provide links between South Australia and Victoria.

The eastern states (New South Wales and Victoria) account for $15.8 billion of costs by 2040. While these states contain a significant portion of the Australian road network (New South Wales with 185,000 kilometers and Victoria with 200,000 kilometers), the cost of protecting these roads is proportionately less than in other states. The reason for this lies in both the reduced physical length of shoreline that is exposed and the difference in geography in this region. In contrast to the significant amounts of low-lying areas found in Western Australia and the Northern Territory much of the east and southeastern parts of the country have a more rapid increase in elevation away from the coastline. Thus, many roads are protected naturally due to the elevation increase.

Finally, Tasmania accounts for the remaining $4.1 billion. The primary reason for this lower amount is the reduced number of roads on the island with a road network totaling 36,000 kilometers. However, this road network has significant exposure around the island with particular exposure in the eastern and northern population centers.

In summary, the national projection for protecting infrastructure from SLR and storm surge ranges from $106 AUD billion in 2040 for a conservative estimate to over $131 AUD billion by 2100 using the same RCP 4.5 scenario. However, these numbers may also be underestimating the cost of protection when compared to the estimates of more extreme climate change scenarios. Additionally, these estimates account for the infrastructure that is in place today. The continued growth in coastal communities would inevitably increase the protection number nationally as additional infrastructure is constructed.

Rank	State	2040 (Billions AUD)	2100 (Billions AUD)	% Increase From 2040 to 2100
1	Queensland	$28.51	$34.73	22%
2	Western Australia	$27.43	$32.29	18%
3	South Australia	$17.85	$20.59	15%
4	Northern Territory	$16.68	$21.50	29%
5	Victoria	$6.45	$8.38	30%
6	New South Wales	$4.95	$7.45	51%
7	Tasmania	$4.14	$5.90	43%
	Total	$106.01	$130.85	23%

Rank	State	2040 (kilometers)	2100 (kilometers)	% Increase From 2040 to 2100
1	Queensland	3,501	4,263	22%
2	Western Australia	2,986	3,539	19%
3	South Australia	1,703	2,017	18%
4	Northern Territory	2,285	2,722	19%
5	Victoria	630	772	23%
6	New South Wales	794	1,172	48%
7	Tasmania	321	458	43%
	Total	12,220	14,943	22%

Tables 1 and 2: Protection cost and length per state at 2040 and 2100 using the RCP 4.5 scenario at the 50th percentile impact. Increase percentage is additional protection required between 2040 and 2100.

Why the Difference in Costs?

The tables presented above document a significant difference in costs in different geographic areas. The complexity of the coastline was highlighted as a leading cause of these differences. However, cost differences ultimately hinge on two additional factors; the length of directly exposed infrastructure, and the infrastructure exposure to both indirect and direct flooding sources. A brief explanation is provided here to provide a general foundation to understand these differences. Appendix A gives a more detailed explanation for one of these high-cost areas, Carpentaria, QSD.

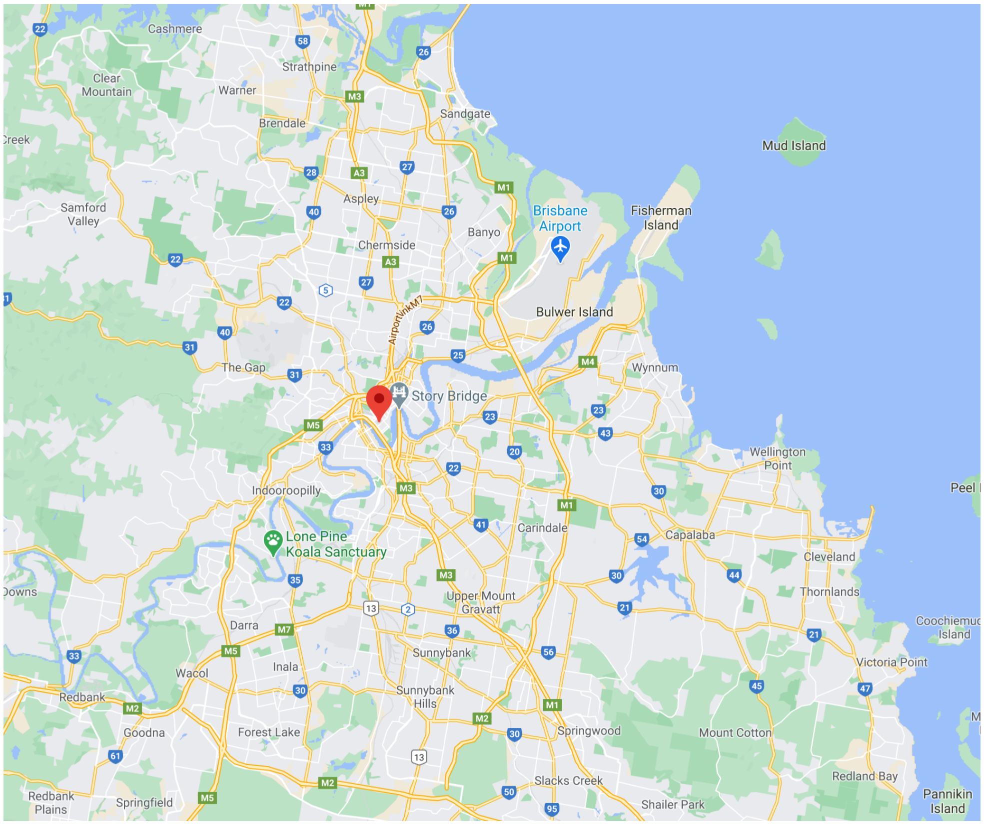

Figure 10: A view of Brisbane illustrating the inland and coastal exposure of the city to SLR and storm surge.

The first example illustrates how coastal areas with both direct coastal exposure as well as inland river exposure results in increased protection costs. As illustrated in Brisbane, the combination of inland rivers and extensive coastal exposure creates a scenario where the

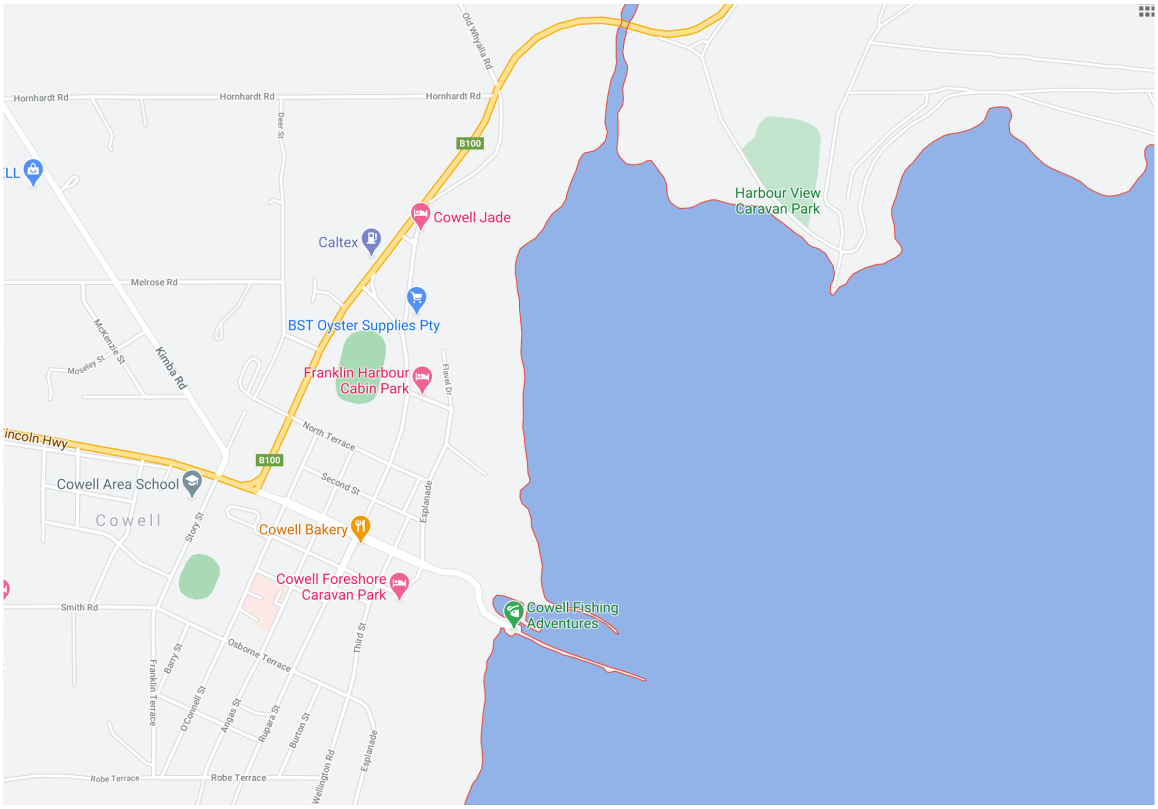

Figure 11: A view of Franklin Harbour, SA illustrating the coastal exposure of the city to SLR and storm surge which creates a high per-capita cost for protection.

city infrastructure is at risk both directly from the coastal exposure and indirectly from the inland flooding that results from water levels rising in the river basin (Figure 10). This combination creates an effect where infrastructure can be exposed from multiple flooding points and thus requires multiple protection points.

In the second case, the scenario exists in local government areas such as Franklin Harbour, SA where the population center is placed along a waterfront and a number of isolated roadways are located along the waterfront throughout the local government area (Figure 11). In these scenarios, protection requirements extend throughout the coastal area to protect infrastructure from SLR and storm surge. The total cost may be limited within the specific population area, but the cost expands quickly as infrastructure built to connect population areas is exposed to SLR and requires protection.

Local Government Area Results

The impact of Sea Level Rise will significantly affect local government areas as localized projections of costs and impacted areas will require action from municipalities in terms of initial expenditures and maintenance costs. In response to this need to highlight costs to local government areas, the study divided the impact costs on a per local government area basis. In addition to total costs, the study places these costs in perspective by allocating costs within local government areas on a per-capita basis. These multiple perspectives provide an indication of the expenditures required as a function of the population in the area as well as the total length of exposure to SLR and storm surge impacts. Table 3 illustrates the Top 20 local government areas by total cost in 2040.

Rank	**County**	**State**	**2040 (Billions AUD)**
1	Carpentaria	QSD	7.75
2	Broome	WA	6.02
3	Karratha	WA	3.91
4	Port Hedland	WA	3.52
5	Gladstone	QSD	3.28
6	West Arnhem	NT	2.68
7	Victoria Daly	NT	2.62
8	Carnarvon	WA	2.54
9	Unincorporated Cox-Daly	NT	2.53
10	Burke	QSD	2.40
11	Yorke Peninsula	SA	2.20
12	Unincorporated Marrakai	NT	1.92
13	West Daly	NT	1.87
14	Derby-West Kimberly	WA	1.79
15	Mackay	QSD	1.77
16	East Arnhem	NT	1.70
17	Port Augusta	SA	1.64
18	Roper Gulf	NT	1.48
19	Ashburton	WA	1.47
20	Livingstone	QSD	1.40
	Total		**54.49**

Table 3: Protection cost per local government area at 2040 using the RCP 4.5 scenario at the 50th percentile impact.

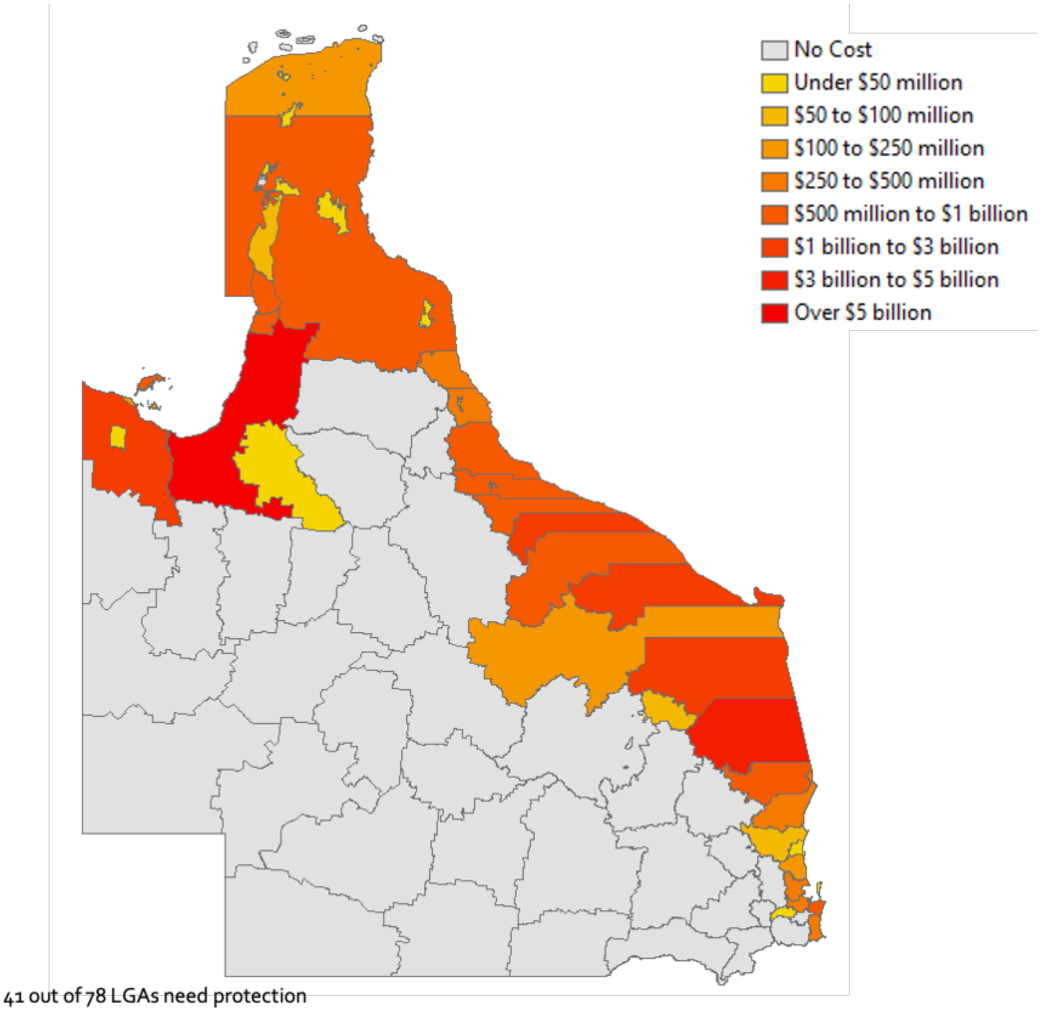

Figure 12: The 2040 projection for Queensland where five of the top twenty local government areas in terms of total costs are located including Carpentaria with the highest total cost for protection in Australia at $7.75 billion.

To illustrate the impact of SLR and storm surge on the local government areas within a specific state, Queensland is shown in Figure 12. Queensland has 5 of the Top 20 local government areas by total cost, reflecting the combination of infrastructure at risk and the length of the Queensland shoreline. Queensland faces a challenge of low-lying areas, extensive exposure to SLR, and multiple areas with coastal infrastructure.

As indicated, Gladstone, Queensland is the second-highest cost local government area in Queensland. However, as opposed to the very rural Carpentaria, Gladstone has a built-up central district. As illustrated in Figure 13, Gladstone highlights the complex combination of extensive infrastructure networks, complex coastline geometry, and extensive population centers. The significant cost to Gladstone places a spotlight on the question of which areas should be protected versus taking a retreat approach and possibly abandoning some areas that are costly due to their location.

In contrast to the populated coastline of Gladstone, the Broome Local Government Area in West Australia illustrates a scenario where a significant amount of infrastructure must be protected along a low-lying peninsula. Figure 14 illustrates the Broome Local Government Area and the major infrastructure that requires protection leading to a total cost factor of $6.02 billion.

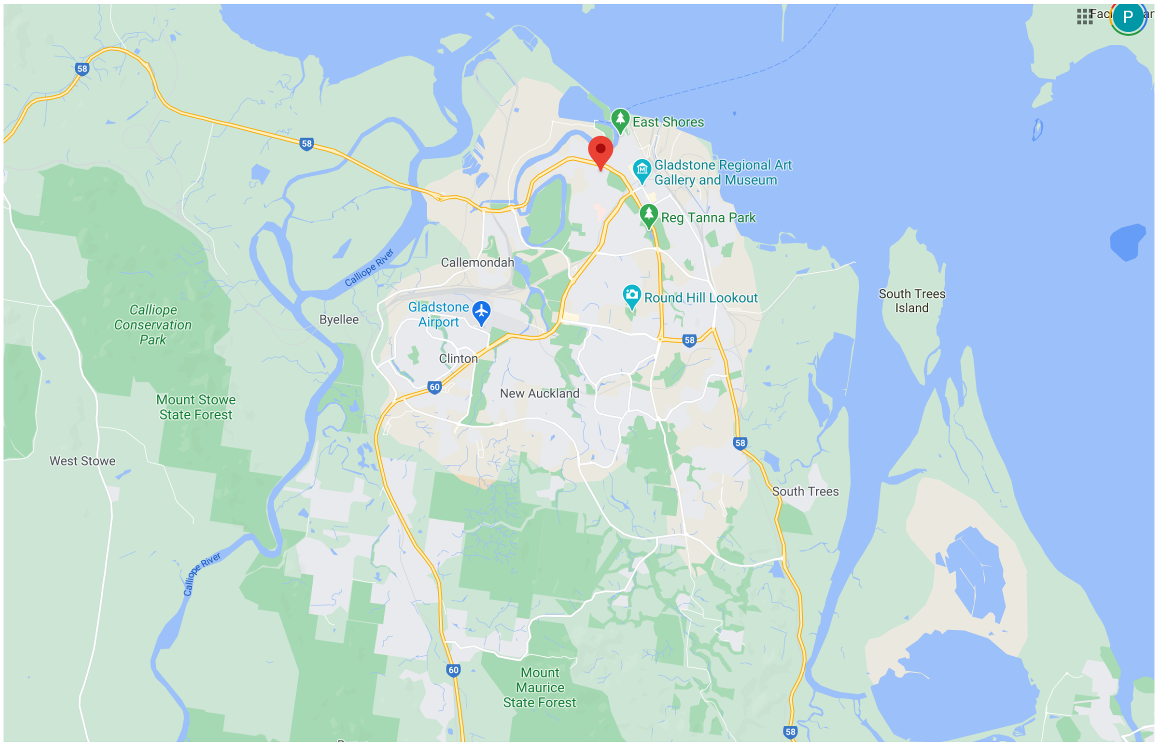

Figure 13: A detailed view of Gladstone, Queensland illustrating the complex policy issue of wat population centers should be protected due to their exposure.

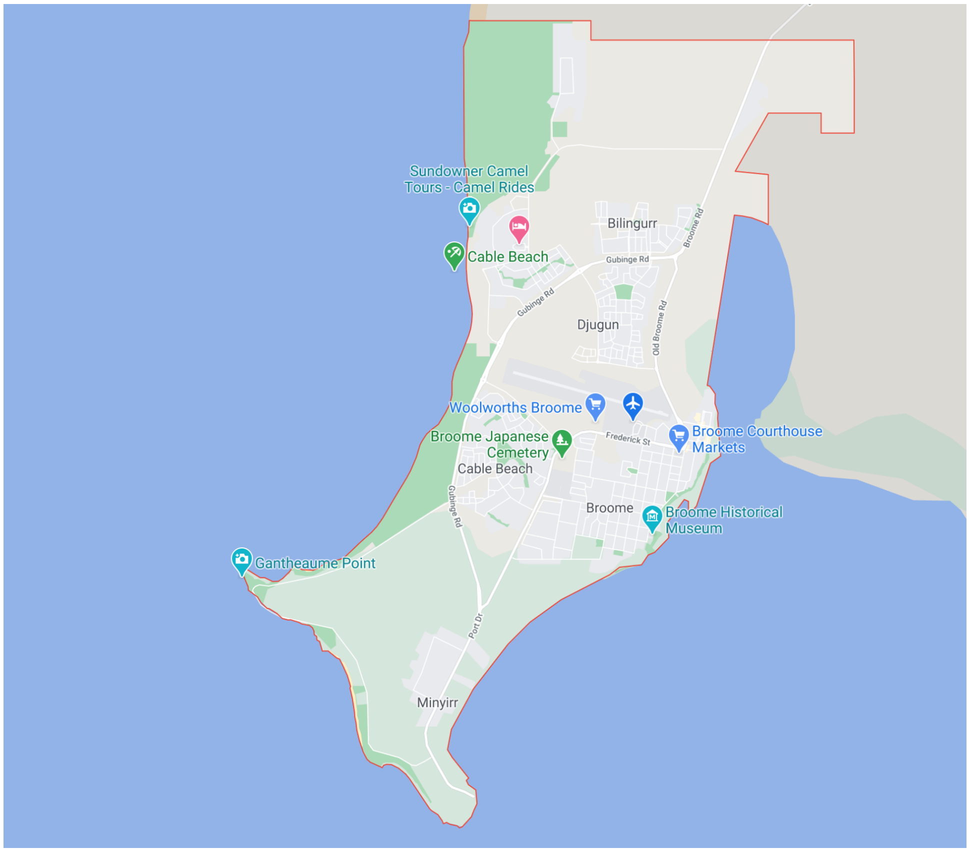

Figure 14: A detailed view of Broome, West Australia illustrating an area where dense population along a coastal area requires large amounts of coastal protection.

As illustrated, the perspective on costs at a local government level can differ depending on whether the concern is total cost, length of protection, or population. These perspectives must be taken into consideration when determining future policies regarding what areas might be given priority for coastal protection. Table 4 illustrates the differences in these perspectives by listing the local government areas by per-capita impact to demonstrate a population density consideration. As illustrated, the populations of these local government areas, place them in an informal category of rural as they have less than 50,000 in population.

Rank	County	State	Population	2040 Per-Capita (Thousands AUD)	2040 Total Cost (Millions AUD)
1	Burke	QSD	354	6,780	2,400
2	Carpentaria	QSD	1,977	3,921	7,751
3	Dundas	WA	714	1,017	726
4	Mornington	QSD	1,230	1,003	1,233
5	Franklin Harbour	SA	1,304	986	1,286
6	Victoria Daly	NT	3,155	830	2,617
7	Kowanyama	QSD	990	819	811
8	Shark Bay	WA	939	681	639
9	Pormpuraaw	QSD	845	639	540
10	Unincorporated (All Areas)	NT	7,376	608	4,485
11	West Daly	NT	3,693	505	1,865
12	Carnarvon	WA	5,182	491	2,542
13	Exmouth	WA	2,871	452	1,299
14	Barunga West	SA	2,563	449	1,152
15	West Arnhem	NT	6,881	390	2,680
16	Broome	WA	16,907	356	6,018
17	Flinders	TAS	1,010	350	353
18	Kingston	SA	2,371	349	827
19	Elliston	SA	1,008	285	287
20	Streaky Bay	SA	2,192	254	558

Table 4: Cost per-capita at the local government area level in 2040 under the RCP 4.5 scenario at 50%

As a contrast, Table 5 lists the local government areas with the largest populations and their equivalent per-capita costs. As illustrated, Queensland has five of the entries and New South

Wales has eight of the entries. The message from Table 5 is that areas with large population areas have a greater population over which to spread the cost impact of adaptation. The greatest cost being in Greater Geelong with $4,009 per capita ($1.04 billion total cost) which is only 2% of the cost of the number 20 entry in Table 4 of $254,000 per-capita.

Rank	Local Government Area	State	Population	2040 Per Capita (AUD)	2040 Total Cost (millions AUD)
1	Brisbane	QSD	1,253,982	205	257
2	Gold Coast	QSD	620,518	654	406
3	Moreton Bay	QSD	469,465	543	255
4	Canterbury-Bankstown	NSW	377,917	4	2
5	Casey	VIC	353,872	923	326
6	Central Coast	NSW	343,968	681	234
7	Sunshine Coast	QSD	328,428	407	134
8	Northern Beaches	NSW	273,499	344	94
9	Wyndham	VIC	270,487	828	224
10	Greater Geelong	VIC	258,934	4,009	1,037
11	Parramatta	NSW	257,197	29	8
12	Sydney	NSW	246,343	19	5
13	Sutherland Shire	NSW	230,611	250	58
14	Ipswich	QSD	222,307	5	1
15	Stirling	WA	221,040	163	36
16	Wollongong	NSW	218,114	222	48
17	Wanneroo	WA	208,237	127	26
18	Lake Macquarie	NSW	205,901	467	96
19	Melbourne	VIC	178,955	120	21
20	Bayside	NSW	178,396	10	2

Table 5: Cost per-square mile at the county level in 2040 under the RCP 4.5 scenario at 50%

The projected costs per population highlight the challenge of small governmental areas in terms of the cost of protection versus the size of the population center. The same challenge exists in terms of the size of the area in comparison to the threats facing the location. Of particular concern, are the coastal areas that either line the coast or lie adjacent to the mainland. This is of particular concern in areas along the Northern Territory coast in particular. These areas often have small populations, but they are popular destinations. Protecting these areas, can translate to significant costs when put in the context of the size of the area.

Discussion

Sea Level Rise and storm surge present a new risk and projected reality for coastal communities. This study highlights a middle-of-the-road projection in 2040 and 2100 to emphasize a likely scenario of costs that states and local government areas will face over the next 5-10 years. Figure 15 illustrates the 2040 and 2100 costs for each state under the conservative RCP 4.5 scenario. As illustrated, the majority of states incur the primary protection costs by 2040 and only a few see significant increases in 2100. Similarly, Figure 16 provides this information in terms of length of protection for each state.

The following sections focus on four primary issues that emerge from the current study: the response timeline, the urban versus rural challenge, the protection feasibility challenge, and the question of replacement versus protection.

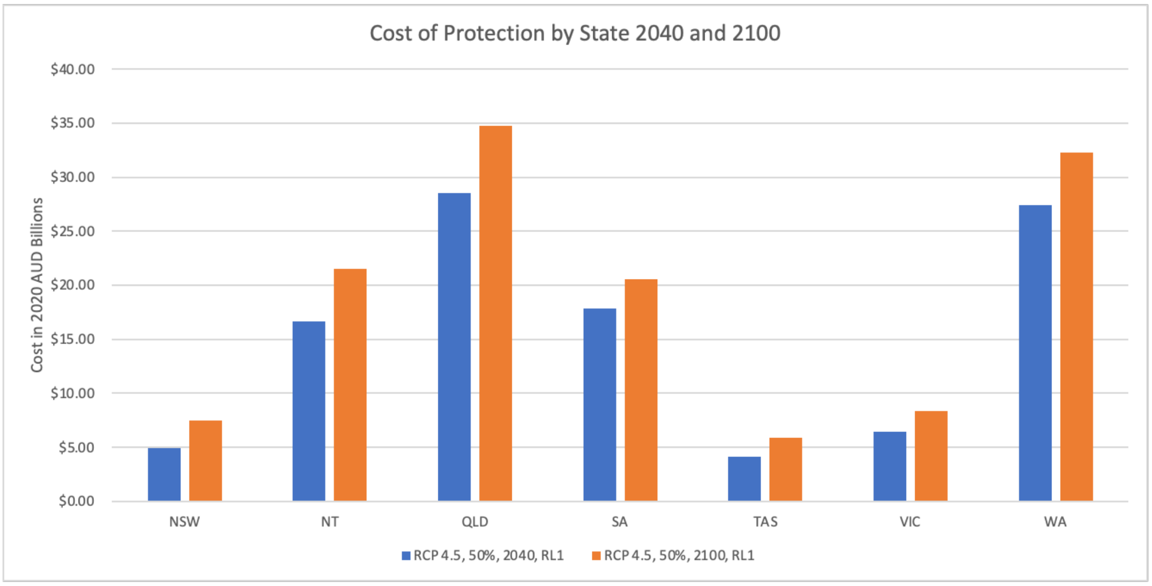

Figure 15: The projections for state costs from the RCP 4.5 scenario at the 2040 and 2100 timeframes for the 50th percentile projections.

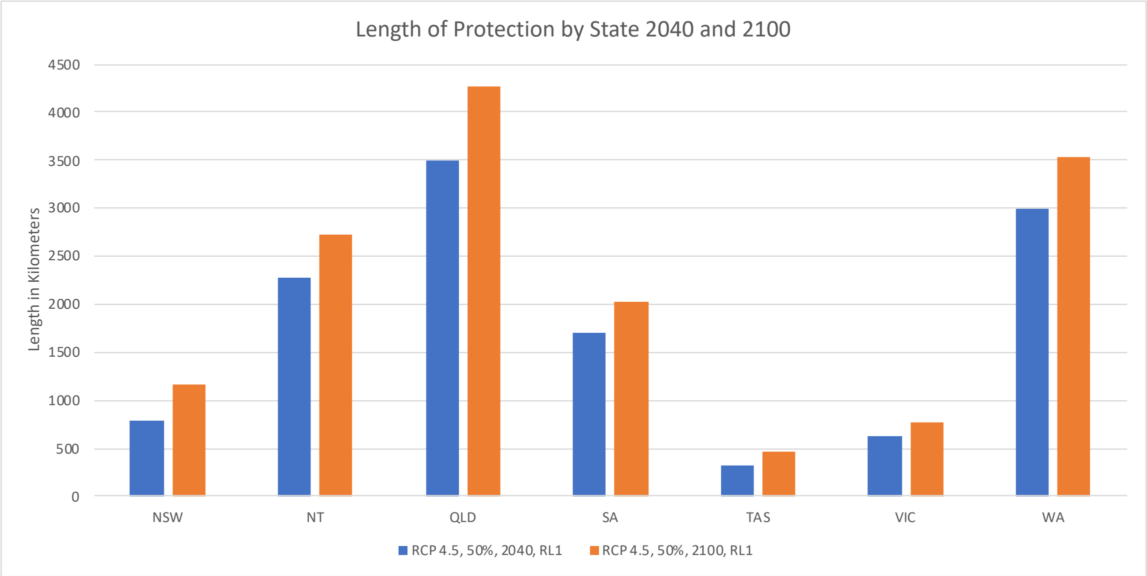

Figure 16: The projections for length of protection by state from the RCP 4.5 scenario at the 2040 and 2100 timeframes for the 50th percentile projections.

Response Timeline

A key message from the data developed in this study is that the timeline for responding to the threat of sea level rise and storm surge begins now. The projected impacts at 2040 indicate that this threat is one that should be included in planning sessions across all affected states. The data for all scenarios included within this study indicate that SLR and storm surge will have a national impact by 2040 in the majority of locations. The projected cost for protecting infrastructure against this impact is expected to exceed $106 billion.

These projected costs of protection are conservative and only focus on the initial construction of the protective barriers. In addition to these totals, consideration must be given to maintenance of the barriers, unforeseen site conditions which complicate construction, and access to locations which may be on private property. These are only a few of the considerations which are likely to increase the final cost for protection.

In addition to the cost factor, there is considerable effort required to plan and design for protective barriers. Issues such as environmental impacts, site-specific engineering solutions, and availability of expertise are issues that will extend the time required to implement protection solutions.

Given that additional cost and time will be required for almost all of the protection projects, consideration must be given to initiating discussions on this issue if they are not already started. The data in this study indicates clearly that within 20 years, approximately 82% of the protection needed by 2100 to protect infrastructure from the SLR risk will already be required. In terms of the number of kilometers of protection required by 2040, there is a projected need for over 12,000 kilometers of protection. This number only increases by 22% to just under 15,000 by 2100.

The message from the data and the accompanying protection analysis is that the timeline for decision-making begins now. The majority of impacts to infrastructure will occur by 2040.

Given the time required to implement a project, communities with projected impacts should consider developing action-response plans sooner rather than later.

Urban versus Rural

The second challenge arising from the current study is the issue of where to prioritize protection from SLR and storm surge. As documented previously, depending on the perspective chosen, the local government areas and cities at greatest risk will change in terms of cost. From a total cost perspective, Carpentaria, QSD ranks number one with a total cost of $7.75 billion. In contrast, Greater Geelong, Victoria is the costliest to protect when the areas with the largest populations are taken into account at approximately $4,000 per-capita. This illustrates the challenge of prioritizing the locations for protection. Should priority be given to total cost of protection, population, or size of area to protect?

The argument for prioritization gets more complicated when the underlying issue of number of assets to protect versus cost of protection is brought to the forefront. Specifically, the question of how to evaluate locations where protection is needed to protect a minimal amount of infrastructure requires further consideration.

The issue of multiple perspectives is highlighted by three local government areas in different top categories. Table 6 provides data for each of the areas from which to draw a comparison. As listed, Greater Geelong, SA is the highest in cost when viewed from a perspective of cost per-square kilometer of land area. This measure indicates that the relative size of Greater Geelong will require a significant investment to protect the infrastructure located in the local government area. In contrast, Clarence Valley has a much smaller investment when viewed on a per-square kilometer basis. This would indicate that the relative cost of protecting the infrastructure in Clarence Valley is less than that facing the area of Greater Geelong.

When viewed from a perspective of population, Franklin Harbour, SA is a much more significant investment than the other two areas. Greater Geelong and Clarence Valley are both smaller investments when placed in the context of a per-capita investment.

Finally, from a total cost perspective, the perspective changes to show that Franklin Harbour and Greater Geelong both require much greater investments than Clarence Valley. From this perspective, Clarence Valley is the lowest cost investment at only $598 million by 2040.

The message in this comparison is that prioritizing investment depends on perspective. Is the greatest priority on population, area that needs to be protected, or total cost? Depending on the perspective chosen, different areas will move to the top of the priority list. Unfortunately, this may place more populated and exposed urban areas in competition with less populated but equally exposed rural areas. The decision as to what to protect must include multiple factors that ensure equal opportunity for each city and town to be protected from the risk of sea level rise and storm surge.

Local Government Area	State	Total Cost 2040 (Millions AUD)	Land Area (Sq. KMs)	2040 Per-Sq.KM (Thousands AUD)	Population	2040 Per-Capita (Thousands AUD)
Greater Geelong	VIC	1,038	1,248	831	258,934	4
Franklin Harbour	SA	1,286	3,283	392	1,304	986
Clarence Valley	NSW	598	10,441	57	51,662	12

Table 6: Comparison of costs at a local government area level through the multiple perspectives of the current study.

Protection Feasibility

The third issue that is highlighted here from the current study is the issue of the feasibility of implementing the required protection by 2040. With 12,000 kilometer of sea wall to construct by 2040, the issue arises as to the feasibility of constructing this volume of protection in time. The issue of feasibility incorporates multiple issues including; availability of design and construction personnel, availability of materials, and the potential from price increases due to micro-inflationary pressures.

In terms of personnel availability, the question focuses on whether there will be sufficient numbers of design and construction personnel available to design and construct over 600 kilometers of sea walls per year for the next 20 years. While there may be sufficient numbers of personnel in locations such as Sydney where coastal engineering is a constant requirement, there may be issues in areas such as the Norther Territory where populations are less dense.

Similar to the availability of personnel is the availability of construction materials. While coastal revetments primarily require rock and concrete which is more readily available, inland bulkhead seawalls require materials such as steel sheet piling. A large push to construct these bulkhead seawalls will put pressure on material suppliers in terms of how the prioritization will be made between seawall construction and the continuing requirements of materials for other projects. Delays in providing materials could stall the required protection projects for extended periods of time.

Finally, the issue of micro-inflationary pressures cannot be overlooked. The cost estimates generated for this project are based on current costs for projects that are developed without the pressure of over-demand. However, large construction projects often increase in price over the estimated cost as external factors including inflation are included (Shane et al 2009). These increases need to be considered during the planning stage as inflationary pressures due to competition for personnel and materials takes hold as the need for protection increases over time.

These are only a few of the factors that will influence the feasibility of implementing the complete set of protection requirements prior to 2040. Additional considerations such as government financing, project prioritization, and new design concepts will likely cause delays and rethinking of where and how to protect infrastructure.

Replacement versus Protection

The final challenge in relation to protecting infrastructure is the relative cost of replacing the infrastructure in a location that is safe from SLR versus protecting that infrastructure from damage. In particular, this challenge arises in remote or sparsely populated areas with limited infrastructure such as in parts of the Northern Territory. In these areas, the financial consideration of protection must be weighed in relation to the costs of rebuilding the infrastructure. Of particular concern in this area are roads. The cost of rebuilding a road will vary depending on the type of road and the location of the road.

Austroads functional road classification divides roads into 9 categories. Class 1, 2 and 3 are rural arterial roads. Class 4 and 5 are rural local roads. Class 6 are highways or motorways. Class 7 are urban arterial roads. Class 8 are urban collector roads. And finally, class 9 are urban local roads (Austroads 2006).

At $5.4 million per-lane kilometer, Class 6 roads are the most expensive and require protection if feasible. Similarly, rural arterial roads are averaging $3.8 million per-lane kilometer making these roads a priority for protection (BITRE 2017). In contrast, Class 4 or 5 rural local roads vary in cost depending on surface type, location, and labor availability among other items. These roads, especially Class 6 specialty roads may be found to be more cost effective to relocate than to protect. Similarly, Class 9 urban local roads may be easier to relocate in some areas with less density than protecting these assets.

The bottom line for decision-makers is to determine which infrastructure assets are financially feasible to protect and which ones need to be considered for relocation or even abandonment.

The overall message for decision makers from these considerations is to undertake planning earlier rather than later. The earlier the planning process begins, the greater the flexibility that communities will have in determining the appropriate actions to take. Historic evidence shows that delaying projects until there is greater demand for the projects will likely result in higher costs.

Conclusion

The current study is intended to open a new conversation on the impact of sea level rise and storm surge. It is not focused on the science behind these risks, nor does it intend to add to the scientific question of whether there will be SLR or how much SLR there might be. Rather, the current study addresses the critical question of what is the impact of the projected SLR and storm surge? At a conservative projection of a $106 billion impact by 2040, SLR can no longer be ignored or treated as a purely theoretical argument by public officials responsible for the health and safety of the general public. The question of how to fund this protection effort must be given the highest priority.

The number of projections that indicate SLR will impact coastal areas within the next two decades should provide motivation for all decision-makers to include this risk in potential hazard discussions. The timeline for impact is now solidly within the planning horizon of public officials at 2040.

In addition to encouraging public officials to include SLR in planning discussions, this study should encourage communities of all sizes to consider the monetary commitment required for protection against SLR. Whether the community is limited in physical area and population, or is one of the larger cities, the impact of SLR will have significant financial impact. It is incumbent on public officials to take an active approach to this potential impact as ignoring it will lead to even greater financial ramifications.

The decision to address SLR is only the first step in addressing this complex issue. A single property owner, or even a single community, is not enough to address the overall threat from SLR. While a single owner may choose to retreat from the coastal area, or a community may elect to aggressively address SLR, this is an issue that requires cooperation and collaboration at the state, regional, and national levels. The successful implementation of a protection system requires neighboring communities and states to work together to ensure that engineered or natural systems work seamlessly along the coastline.

Additionally, prioritization must be considered when implementing any protection plan. The question of how to develop this prioritization is one with no easy solution. However, public officials have a choice; focus on the differences between the communities (size, population, total risk), or focus on possible solutions that can be mutually beneficial. The choice that is made will set the stage for the future of many communities.

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Appendix A: Example of High-Cost Rural Area

A critical question in determining long-term actions that should be taken to adapt to sea level rise is what areas should be protected and at what financial cost. Carpentaria, QSD is a good example of this question. As the highest cost local government area at over seven billion dollars to protect, and with a population of less than 2,000, should this area be protected? While the answer to this question is a policy concern, it is important to detail why the projected costs in these areas are so high.

As illustrated, Carpentaria has a very large network of roads. Many of these roads are dirt roads that serve a specific purpose or are only used by a limited set of individuals. However, from a protection perspective, all roads are important as they serve specific functions and support other infrastructure. Where this gets expensive is in an area like Carpentaria where the coastline is complex and is also low-lying. This combination leads to extensive exposure to flooding and inundation.

Given this exposure, protecting the infrastructure requires an extensive set of flood barriers to ensure that all potential flooding points are addressed. As illustrated, this can be an extensive network to address each inlet in the area. Is it necessary to put all of the protection in place? It is necessary of the goal is to protect the roads and other infrastructure from flooding. However, in the end this is a risk and policy question. What will remain is the physical risk that exists, and this is what is captured by the results in this report.

Carpentaria: Area of Carpentaria in light brown, coastline in light blue, flooded area in dark blue, and horizontal infrastructure in black. Almost all roads are dirt. High costs are a combination of rural dirt roads and a very low lying and complex coastline.