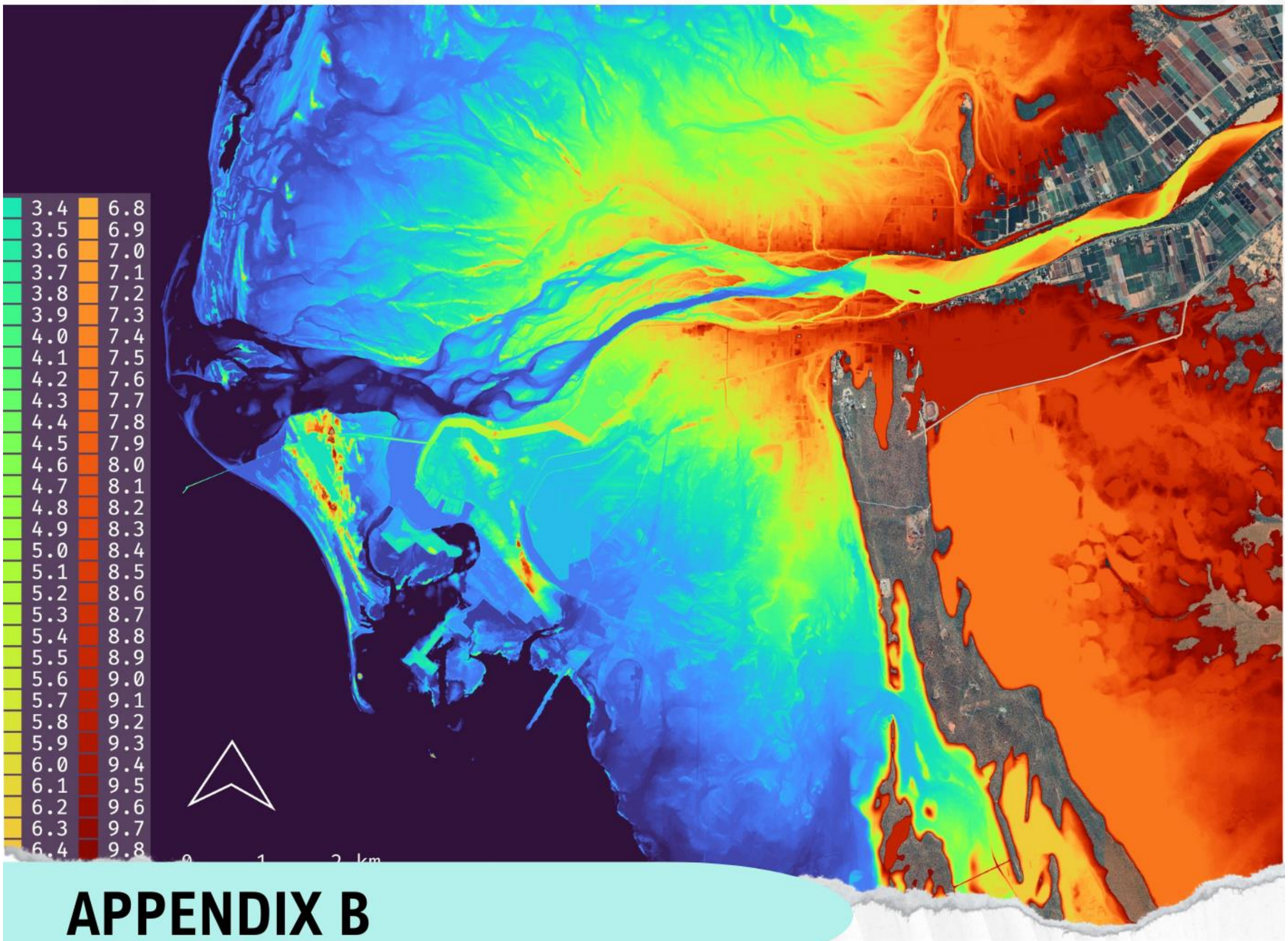
A Statewide Coastal Inundation Assessment for WA



APPENDIX B

TECHNICAL METHOD

Seashore Engineering

coastwa

Government of Western Australia
Department of Planning, Lands and Heritage
Department of Transport

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Limitations of this Report

This report and the work undertaken for its preparation, is presented for the use of the client. The report may not contain sufficient or appropriate information to meet the purpose of other potential users. Seashore Engineering does not accept any responsibility for the use of the information in the report by other parties.

Appendix B: Coastal Inundation Assessment Method

1.1 Water Level Recurrence Evaluation

Extreme still water level values for the WA tide gauge network were defined through extreme event analysis over their respective records. This evaluation followed a review of existing extreme water levels which identified inconsistencies between LGA sites limiting their application for a Statewide assessment.

Approach:

- Identification of water level peak above thresholds from selected digital tide gauge records within a 48-hr period intended to capture storm passage over at least two tidal peaks. Significant events which were not recorded in the digital tide gauge records were included where reliable water level estimates were deemed to exist (e.g. TC Alby: Bunbury historic gauge value, TC Vance: Onslow wrack line).
- Water level peaks were detrended to account for relative sea level rise; A linear best fit applied to the long-term Fremantle record has been used across the state, noting that fits from the shorter water level records have significant influence from several periods of unprecedented high mean sea levels since 1999 correlated to the ENSO cycle, evident in the Fremantle observations.

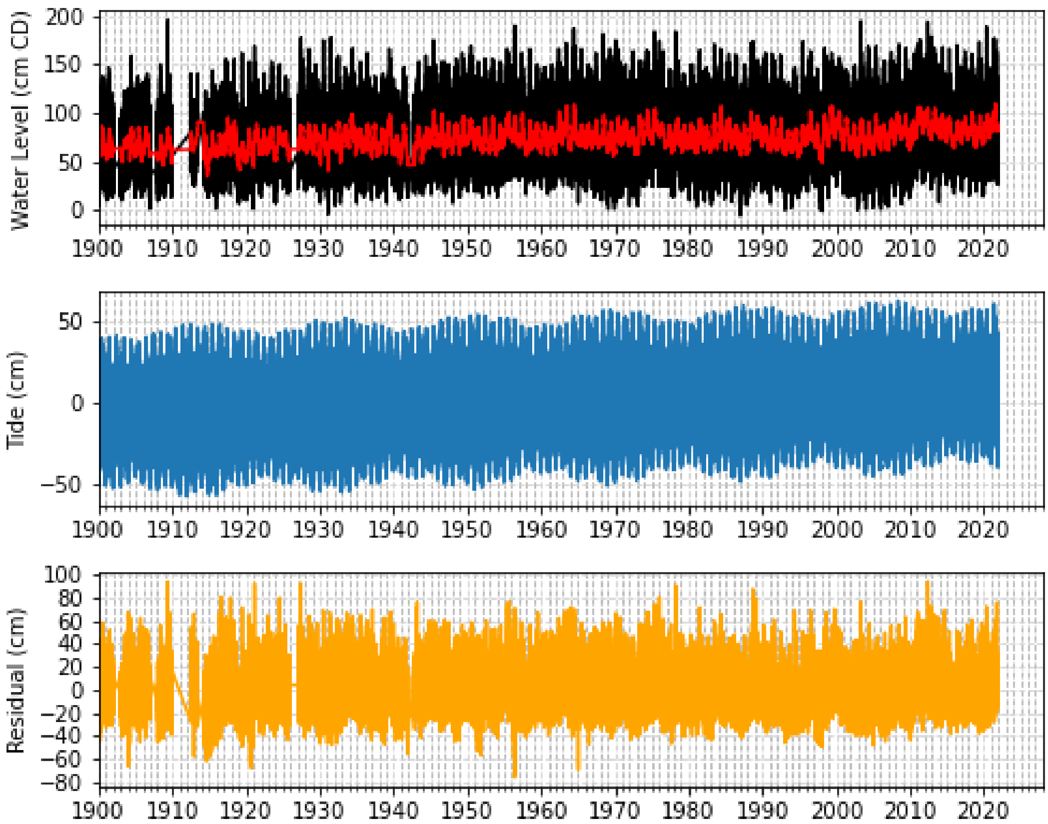

Figure 0-1: Fremantle water level observations
Includes 30 day running mean sea level (red), tide and residual components.

- Extreme distributions were fitted to peak water levels using the method of Petrauskas & Aagaard (1971) to obtain average recurrence intervals (ARIs), with examples below for Fremantle: longest available record, and Port Hedland: cyclone region; and all sites provided in Appendix A. Extreme fitting parameter (k) was adjusted depending on the nature of the events, with generally lower k values (steeper curves) used for tropical cyclone areas and for the residuals fits.

- Three distributions were derived for each site.
  a) All 'high' water level peaks (black line Figure 0-1), with number of events set to match the length of record in years.
  b) Water level peaks filtered to include only the 'high' residual events, with number of events also set to match the length of record in years (orange line).
  c) Water level peaks filtered to include only the most 'extreme' residual events, with number of events set as half the length of record in years (red line). In cyclone areas, this typically ensures only water levels recorded during cyclone passage contribute to the distribution.

- The maximum water level for the three distributions at each ARI was chosen as the extreme water level value. For example, at Fremantle, the unfiltered water level distribution (black) contributed to ARIs <20yrs, transitioning to extreme (red line in Figure 0-2) for ARIs >30yrs.

- Where the WA tide gauge network was considered not to provide adequate representation of a site, interpretation of existing information was used as a basis for interpolating between nearest tide gauges. This included use of levels defined from Carnarvon at Denham; factoring levels defined from Dampier (King Bay) by 1.15 to account differences in tide and surge response in Nickol Bay based on typical differences identified in Canute 3.0 extreme water level values; and use of the average of levels defined for Busselton and Albany for Augusta where a lack of information on water levels was available.

Limitations:

Although water levels defined are considered suitable for use in a regional assessment of coastal inundation across Western Australia, there are several limitations which include:

- Levels defined are sensitive to the nature of the events recorded in the tide gauge network, with particularly high sensitivity for those in cyclone events.
- Analyses based on historic observations generally have low confidence when estimating the magnitude of events with ARI's more than 2-3 times the duration of an observational data set. For Exmouth, this means increasing uncertainty when estimating water levels with a recurrence of longer than ~75 years.
- Wave run-up is not included which is an important inundation processes for areas with a relative absence of foreshore buffer.
- Water levels reported are intended as fit-for-purpose based on best available information for the strategic prioritisation presented here. **They are not intended as a basis for engineering design and should NOT be applied as such.**

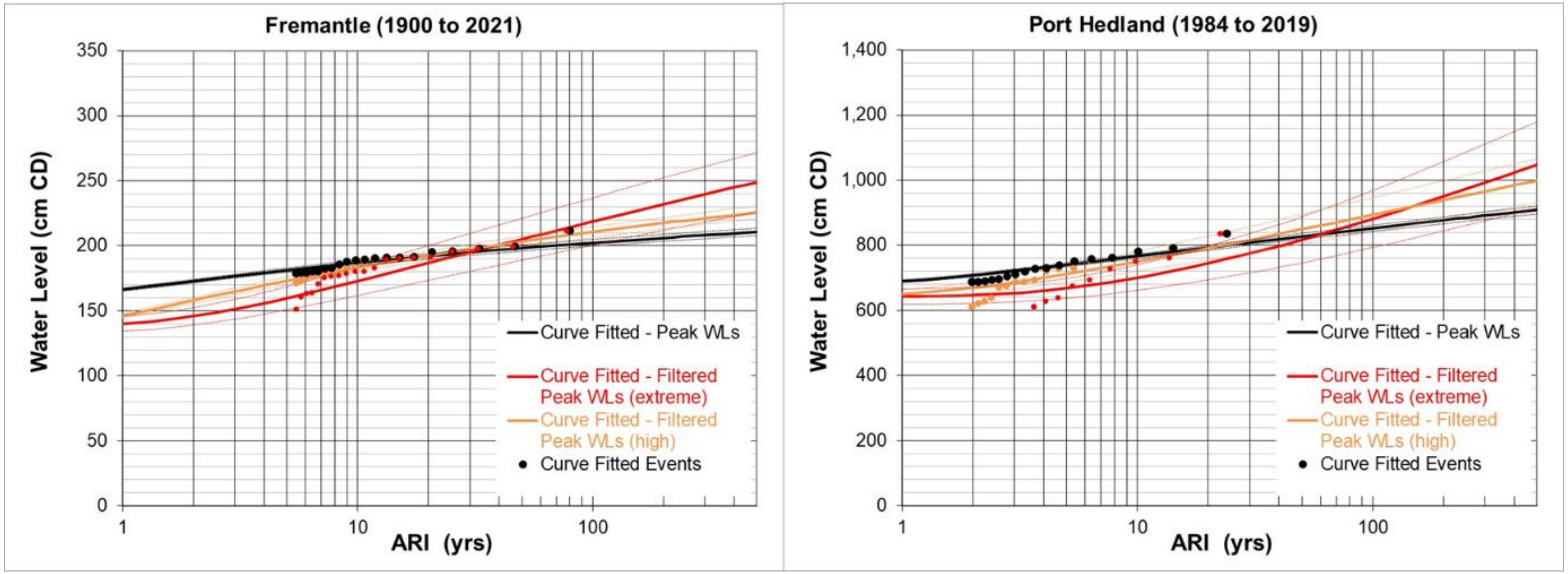

Figure 0-2: *Water level recurrence evaluation*

Annual Recurrence Intervals and Annual Exceedance Probability

Average Recurrence Interval (ARI) and Annual Exceedance Probability (AEP) are different ways of describing how often or likelihood a water level occurs.

What is the Average Recurrence Interval?

ARI is used to communicate the typical length of time between occurrences of a given sea level. It is implicit that time between exceedances is generally random, and this time may be much shorter or longer, depending on conditions experienced.

ARI is alternately called "return period". Common misinterpretations are that ARI implies regular intervals (cycles) between events or that extreme levels can only occur once within the given length of time. Instead, they can happen once, multiple times, or not at all. For example, in any given year there is a 1% chance that a 100 year ARI water level could be reached. However, occurrence does not modify the behaviour of subsequent events, and it is possible for multiple 100 year ARI events to occur within a single year.

What is Annual Exceedance Probability?

AEP is defined as the probability or likelihood that a given water level will be exceeded in any one year.

How does AEP relate to ARI?

With ARI expressed in years, the relationship is:

$$\text{AEP} = 1 - \exp\left(\frac{-1}{\text{ARI}}\right) \quad (1)$$

Likelihood of exceedance increases over multiple years (Y), indicated by the relationship:

$$\text{EP} = 1 - \exp\left(\frac{-\text{Y}}{\text{ARI}}\right) \quad (2)$$

ARI has been used in this study for consistency with most coastal inundation studies reported previously for WA LGs.

Relationship between Average Recurrence Interval (ARI) and Annual Exceedance Probability (AEP) through time

ARI	AEP	Time Frame Considered (years)						
(years)	(per year)	1	2	5	10	25	50	100
0.5	86%	86%	98%	100%	100%	100%	100%	100%
1.0	63%	63%	86%	99%	100%	100%	100%	100%
1.5	49%	49%	74%	96%	100%	100%	100%	100%
2.0	39%	39%	63%	92%	99%	100%	100%	100%
3.5	25%	25%	44%	76%	94%	100%	100%	100%
5.0	18%	18%	33%	63%	86%	99%	100%	100%
10	10%	10%	18%	39%	63%	92%	99%	100%
20	5%	5%	10%	22%	39%	71%	92%	99%
35	3%	3%	6%	13%	25%	51%	76%	94%
50	2%	2%	4%	10%	18%	39%	63%	86%
100	1%	1%	2%	5%	10%	22%	39%	63%
200	0.5%	0%	1%	2%	5%	12%	22%	39%
500	0.2%	0%	0%	1%	2%	5%	10%	18%

1yr ARI has a ~63% probability of being equalled or exceeded in any one year, but a 99% probability of occurring or a 1% probability of not occurring over a 5 year period of observation.

20yr ARI has a ~5% probability of being equalled or exceeded in any one year, and a 39% probability of occurring or a 61% probability of not occurring within 10 years.

100yr ARI has ~1% probability of being equalled or exceeded in any one year, and a 22% probability of occurring or a 78% probability of not occurring over 25 years.

100yr ARI + 0.9m has been used as an upper limit event, to consider sensitivity to extreme water levels. 0.9m was selected due to its use as an allowance for projected sea level rise in long-term planning, although the inundation risk assessment does not consider sea level rise *per se*.

Derived water level average recurrence value for selected WA tide gauges (m AHD)

Tide Gauge	Years of Data	Min Year	Max Year	2yr ARI	5yr ARI	10yr ARI	20yr ARI	**25yr ARI**	50yr ARI	**100yr ARI**	200yr ARI	500yr ARI
Broome	30.8	1991	2023	4.32	4.70	4.96	5.20	5.27	5.48	5.79	6.23	6.81
Port Hedland	34.8	1984	2019	3.19	3.51	3.77	4.04	4.16	4.60	5.05	5.59	6.58
King Bay	34.5	1982	2021	2.21	2.45	2.66	2.91	2.99	3.29	3.66	4.14	4.83
Onslow	36.2	1985	2022	1.58	1.83	2.06	2.36	2.47	2.89	3.45	4.06	4.92
Exmouth	26.0	1989	2020	1.42	1.68	1.91	2.18	2.27	2.62	3.08	3.58	4.31
Carnarvon	45.5	1966	2021	1.26	1.38	1.48	1.63	1.69	1.90	2.10	2.37	2.74
Geraldton	55.3	1966	2021	0.97	1.07	1.16	1.26	1.30	1.44	1.60	1.77	1.99
Jurien	29.3	1991	2020	0.83	0.91	0.96	1.03	1.06	1.13	1.19	1.27	1.40
Barrack Street	31.9	1988	2022	0.94	1.00	1.04	1.10	1.12	1.20	1.29	1.37	1.48
Fremantle	111.8	1900	2021	0.96	1.04	1.10	1.15	1.18	1.28	1.42	1.55	1.72
Peel	24.9	1994	2020	0.82	0.90	0.95	1.02	1.04	1.10	1.18	1.25	1.35
Mandurah	29.1	1990	2020	0.81	0.89	0.94	0.99	1.00	1.08	1.16	1.24	1.33
Bunbury	35.9	1985	2020	1.13	1.29	1.40	1.54	1.58	1.77	1.94	2.10	2.31
Busselton	19.8	2002	2020	1.35	1.50	1.61	1.77	1.82	1.98	2.14	2.30	2.51
Albany	32.6	1987	2020	0.95	1.00	1.04	1.07	1.08	1.12	1.17	1.22	1.27
Esperance	36.2	1987	2023	1.20	1.25	1.29	1.33	1.34	1.37	1.42	1.48	1.54

Distribution	
	Unfiltered Distribution: High Water Levels
	Filtered Distribution 1: High Residuals
	Filtered Distribution 2: Extreme Residuals

1.2 Establishing a Topographic Database

Ground levels play a critical role in evaluation of coastal inundation risk, influencing the propagation of water and defining flood levels where people or assets may be affected. Digital Elevation Models (DEM) approximate the ground surface with different levels of vertical and horizontal resolution, depending on how the area was surveyed and subsequent treatment. Collation of existing government captured datasets has previously been undertaken by Department of Fire and Emergency Services, for production of coastal inundation risk maps, with collation of additional information by Department of Transport as part of the Coastal Inundation Management Review. Most LGAs completing CHRMAP have incorporated high resolution LiDAR surveys in their assessments (Table below).

Salient characteristics of available data relevant to the hazard assessment include:

- Denham Northampton, Geraldton, Coorow, Dandaragan and Gingin are sites with topographical resolution exceeding the optimal 1m level.
- For sites between Cape Naturaliste and Lancelin, captured by LIDAR in 2008/9, these areas have been subject to coastal change since this capture, demonstrating the need for careful use of older data.

Overall, suitable high resolution topographic can be accessed for all LGAs under consideration (with the exception of Shark Bay). The statewide inundation hazard assessment is therefore based on the best available topographic information (LIDAR) for a study of this kind.

1.3 Identifying Inundation Exposure Areas

Phase 1 considered each of the 47 coastal LGAs for WA and rated their exposure to coastal inundation hazard as none, low, medium or high. This assessment was based on a simple bathtub visualisation assessment for a 100yr and 500yr ARI (e.g. Figure 0-3) and, where possible, validation through consultation with LGAs. In total, 23 LGAs were rated as either 'medium' or 'high' exposure and selected for more targeted consideration through Phase 2.

Information collated through Phase 1 was re-evaluated to determine the spatial distribution of potential inundation within each of the selected Local Government Areas. This involved:

- Visual assessment of mapped inundation levels in conjunction with cadaster/land boundary information available for each LGA to determine a locally relevant scale.
- Consideration of physical setting (geology, geomorphology and specific land elevations) as well as likely local mechanisms of flooding to determine where there were separate, discrete areas potentially subject to inundation.

Table 0-1 Inundation Exposure Areas (IEAs) per LGA:

	LGA	Location	Population	Total Area (km^2]	# of IEAs
1	Shire of Broome	Kimberley	16,959	54,400	2
2	Town of Port Hedland	Pilbara	15,684	18,417	3
3	City of Karratha	Pilbara	22,199	15,237	1
4	Shire of Ashburton	Pilbara	7,391	100,818	1
5	Shire of Exmouth	Gascoyne	3,085	6,488	3
6	Shire of Carnarvon	Gascoyne	5,251	46,575	4
7	Shire of Shark Bay	Gascoyne	1,031	24,201	1
8	Shire of Northampton	Midwest	3,227	12,544	1
9	City of Greater Geraldton	Midwest	39,489	133,061	4
10	Shire of Coorow	Midwest	1,055	4,190	2
11	Shire of Dandaragan	Wheatbelt	3,355	6,712	2
12	Shire of Gingin	Wheatbelt	5,576	3,208	4
13	City of Fremantle	Perth Metro	31,930	19	2
14	City of Rockingham	Perth Metro	135,678	258	2
15	Shire of Murray	Peel	90,306	175	5
16	City of Mandurah	Southwest	18,068	1,704	3
17	Shire of Harvey	Southwest	28,567	1,728	1
18	City of Bunbury	Southwest	32,987	65	2
19	Shire of Capel	Southwest	18,175	558	1
20	City of Busselton	Southwest	40,640	1,454	7
21	Shire of Augusta/Margaret River	Southwest	16,791	2,122	1
22	City of Albany	Great Southern	38,763	4,311	2
23	Shire of Esperance	Goldfields	13,883	44,798	3
	Total # of IEAs				**57**

1.4 Percolation Assessment

A percolation assessment using high resolution topographic data was completed for each segment at 0.1m increments, ranging from 0m AHD to 10m AHD data, shown in maps developed for each site, illustrating three selected inundation levels, along with key inundation pathways. An example for the City of Bunbury is provided here to demonstrate the percolation process and later the AEIP assessment.

Steps in this percolation process included:

1. Estimation of average recurrence interval for inundation
2. Visualisation of existing high-resolution LIDAR data to identify presence of thin barriers which restrict inundation pathways to lower land, or narrow channels which may provide opportunity to mitigate hazard. For example, barriers to lower land landward of the Onslow Seawall and Lancelin dune system were identified.
3. Ensuring the gridding of high-resolution topography used at each site is at a scale that avoids 'merging' of thin features.
4. Complete a 'percolation' approach, to determine the potential flooding extent, at 0.1m elevation increment, from 0m to 10m AHD. This was undertaken using a nearest neighbour algorithm, starting from an ocean corner, subject to the condition that any adjacent points below the nominated percolation elevation threshold is tagged as inundated.

Inundation Mapping

Percolation for each of the sites used to map indicative **~25yr ARI**, **~100yr ARI** and **~100yr+0.9m** water levels based on the tide gauge analysis conducted for this study. Importantly, these water levels are intended as a guide to demonstrate indicative areas at risk of potential inundation.
Primary inundation entry points are illustrated on each map. These are intended to show key points of entry of coastal flood waters and in some cases points of spreading.

In the example below from Bunbury, primary pathways are identified through 'The Cut' into Leschenault Estuary where low lying areas around Estuary Drive are likely to be inundation at a ~25yr ARI level and 'The Plug' in Koombana Bay adjacent to Bunbury townsite with multiple spreading points within the Leschenault inlet at an inundation level of 1.6m AHD.

Overall, the hazard maps show the potential extent of inundation for exposed locations and act as a tool to interpret the potential nature of inundation impacts to assets.

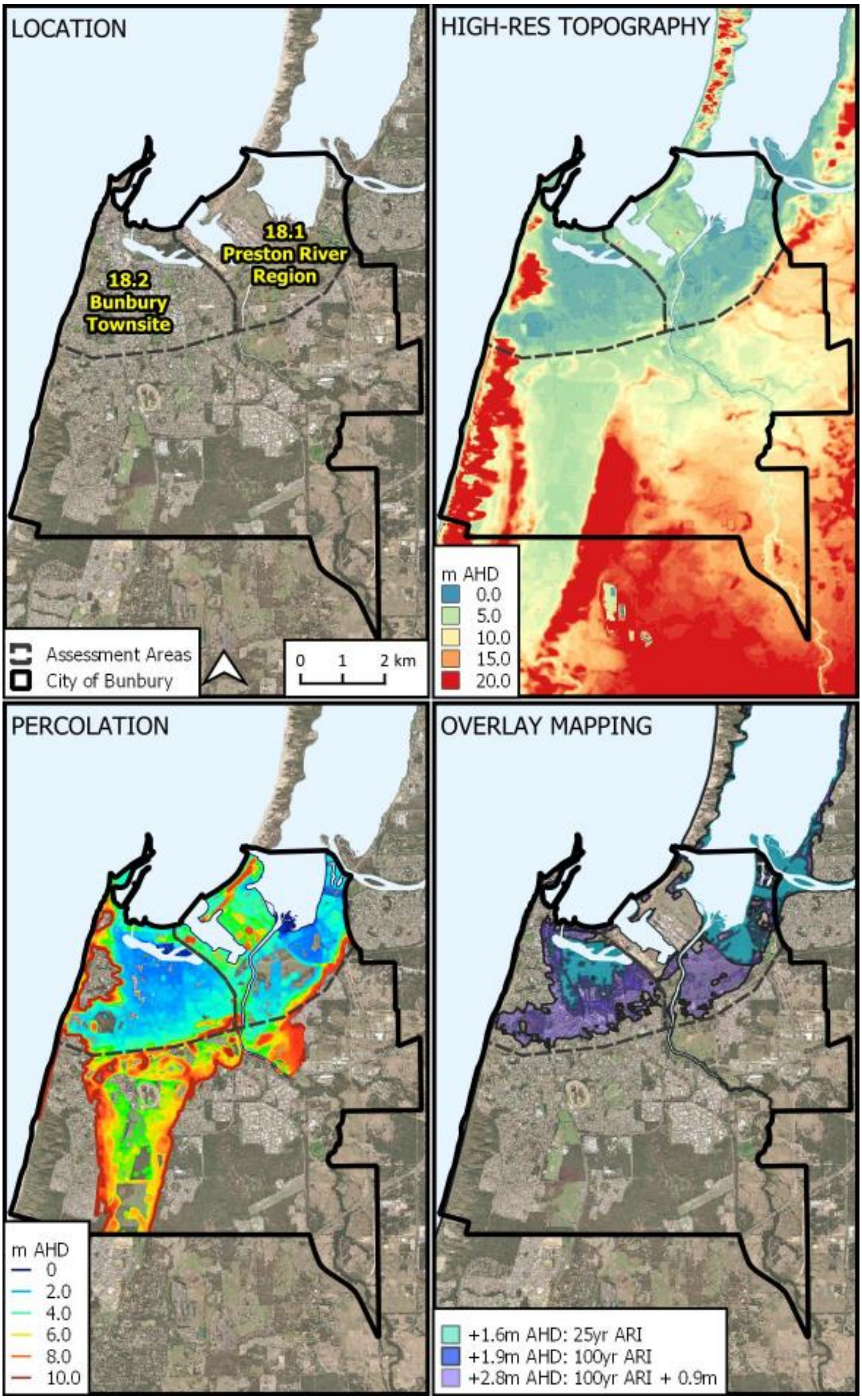

Figure 0-3: Example of Inundation assessment process for Bunbury
Delineation of site specific segments for analysis; collation of high resolution topography; percolation assessment; delineation of inundation areas for the 25yr ARI, 100yr ARI and 100yr ARI +0.9m

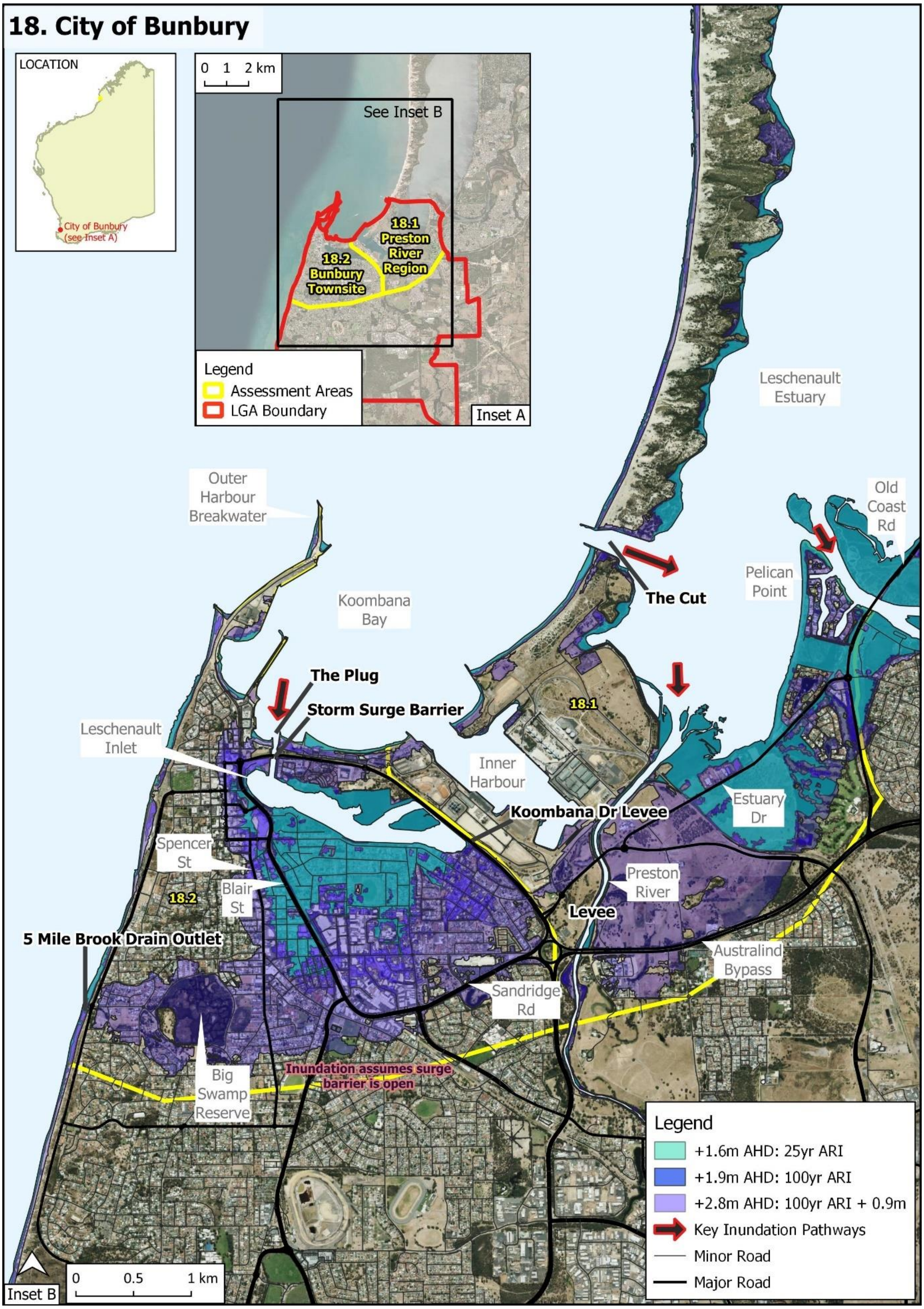

Figure 0-4: Example inundation map for Bunbury Townsite and Preston River Region

1.5 Asset Assessment: Financial Exposure

AEIP[a] Analysis

The set of shapefiles outputted from the percolation and hazard assessment were submitted to the Australian Exposure Information Portal (AEIP) facilitating interrogation of the NEXIS database. The NEXIS database includes information obtained from WA Valuer General, for both government and private assets, across Western Australia.

The AEIP tool produced a range of exposure information. Primary exposure included financial building counts and reconstruction costs for residential, commercial, and industrial buildings, as well as roads (major and arterial). In addition, exposure across several additional categories, was recorded and reported on qualitatively where relevant:

- Airports (count)
- Railway track (km)
- Schools (count)
- Wastewater Treatment facilities (count)
- Agricultural land (Ha)

It is acknowledged that for privacy reasons, the AEIP tool does not provide residential reconstruction values when residential building counts are below 20. Where applicable, a correction based on unit value once building exposure first exceeds 20 has been included in damage values used to support site prioritisation, however no correction is applied to values presented in the individual site summaries. Key exposure information was collated and tabulated to a range of critical inundation levels (relative to AHD) for each assessment area, including indicative highlighted levels for the 25yr ARI, **100yr ARI** and **100yr ARI +0.9m** based on water level recurrence evaluation.

Exposure tables are presented within each of the Site Summaries except where no assets were identified as exposed under the range of inundation levels considered. An example is provided for the City of Bunbury in the southwest of the State where two inundation exposure areas were assessed:

18.1 Preston River Region
18.2 Bunbury Townsite

[a] The Australian Exposure Information Platform tool is a Geoscience Australia (GA) tool that utilises the National Exposure Information System (NEXIS).

	Inundation Level (m AHD)	18.1 Preston River Region			18.2 Bunbury Townsite		
		Residential Buildings	Commercial /Industrial Buildings	Roads Major/Arterial (km)	Residential Buildings	Commercial /Industrial Buildings	Roads Major/ Arterial (km)
	1.1	0	0 / 0	1 / 1	1	0 / 0	0 / 1
	1.2	1	0 / 0	1 / 1	4	0 / 0	0 / 1
	1.3	1	0 / 0	1 / 1	217	0 / 0	0 / 1
	1.4	1	0 / 0	1 / 2	334	0 / 0	0 / 1
	1.5	1	0 / 0	1 / 2	449	2 / 0	0 / 1
~25yr ARI	1.6	3	0 / 1	1 / 2	558	71 / 0	0 / 3
	1.7	3	0 / 2	1 / 3	646	107 / 0	0 / 3
	1.8	3	0 / 2	1 / 3	787	160 / 0	0 / 5
~100yr ARI	1.9	3	0 / 2	1 / 3	927	202 / 0	0 / 6
	2.0	5	0 / 9	2 / 4	1048	244 / 0	0 / 6
	2.1	5	0 / 9	3 / 4	1243	288 / 0	0 / 8
	2.2	6	0 / 14	3 / 4	1390	328 / 1	0 / 9
	2.3	7	0 / 15	3 / 4	1591	370 / 1	0 / 10
	2.4	23	0 / 17	3 / 4	1891	409 / 1	0 / 12
	2.5	53	0 / 19	3 / 5	2075	422 / 1	0 / 13
	2.6	137	0 / 20	3 / 5	2209	441 / 1	0 / 15
	2.7	202	0 / 20	4 / 5	2311	457 / 1	0 / 16
~100yr ARI + 0.9m	2.8	287	0 / 20	4 / 5	2410	477 / 1	0 / 17

Figure 0-5: AEIP Asset exposure; Preston River & Bunbury Townsite

AEIP asset exposure tables for Bunbury indicate:

18.1 Preston River Region:

- The majority of residential building exposure occurs above an inundation level of 2.4m AHD, with first exposure of an industrial building identified at 1.6m AHD (~25yr ARI) increasing to 20 buildings at 2.8m AHD (100yr ARI +0.9m). In total, 9km of road is exposed at 2.8m AHD.

18.2 Bunbury Townsite:

- Exposure for this segment assumes the Bunbury Storm Surge Barrier is open (effective up to ~2.2m AHD), allowing for relatively widespread flooding around the Leschenault Inlet commencing at about +1.3m AHD. This results in exposure of a relatively large number of residential buildings from 1.3m AHD (217), increasing to over 500 buildings at 1.6m AHD (~ 25yr ARI), over 1000 at the 1.9m AHD (~ 100yr ARI) and close to 2500 buildings at 2.8m AHD (~100yr ARI +0.9m).
- A high number of commercial buildings are also exposed from the 1.6m AHD upwards increasing to over 200 buildings at 1.9m and almost 500 buildings by 2.8m AHD. A total of 17km of road will be exposed in the townsite by a 2.8m AHD inundation level as well as an ambulance station, 3km of rail track, a retirement home and 4 schools**.**

To further demonstrate vulnerability of assets to inundation hazard for each of the sites, the sum the reconstruction values for residential, commercial and industrial provided by AEIP (i.e. value of exposed assets) at each 0.1m interval has been plotted along with the likelihood of inundation occurrence, represented as average annual exceedance probability based on water level recurrence evaluation (Figure 0-6).

For Bunbury, overlap of likelihood curves with significant value of exposed assets broadly indicates high vulnerability to inundation, particularly between 1.5-2.5m AHD, which is the steepest slope of the exposed asset curve. At +1.9m AHD (~100yr ARI, Figure 18. City of Bunbury), there is $2.5 billion of exposed assets, which is a 22% of being impacted by inundation over 25years.

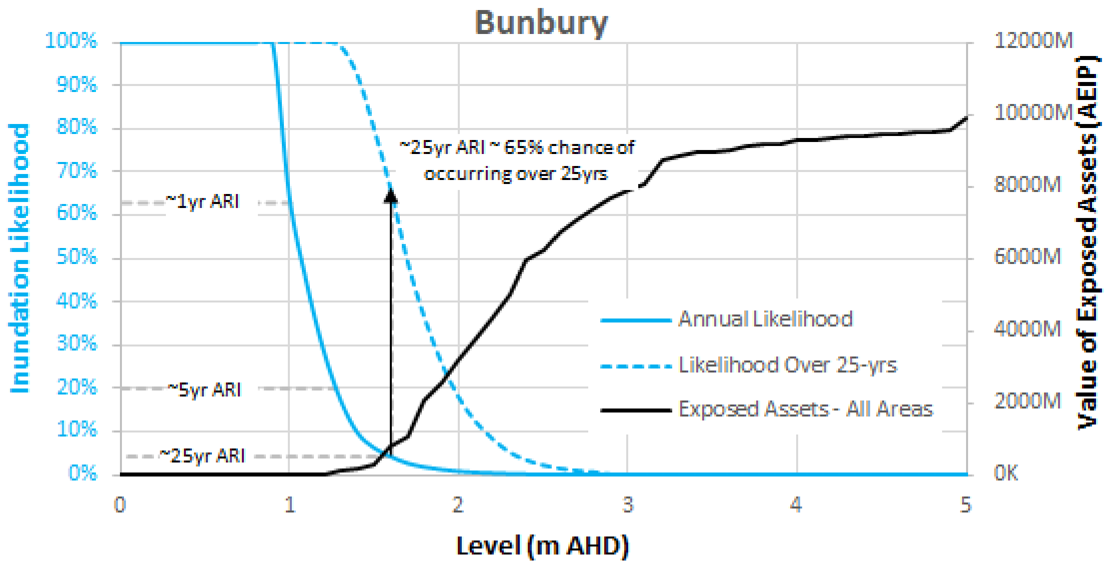

Figure 0-6: Inundation likelihood versus asset exposure, Bunbury

1.6 Inundation Risk

Indicative estimates for annualised damage costs associated with each 0.1m inundation increment was derived through integration of financial exposure, with depth-damage fraction curves (Appendix B) and inundation likelihood, as follows:

$$Risk_{Ann} = \int_{Min\ h}^{Max\ h} p(h).Dam(h).dh$$

Where:

- p(h) is the probability of being above an inundation threshold h, defined from water a recurrence evaluation.
- Dam(h) is the estimated financial cost from an inundation event reaching each inundation threshold, which is calculated through reconstruction values for residential, industrial and commercial categories and their corresponding depth damage curves.

Damage curves were further integrated with estimates of inundation likelihood, to estimate average annual damage. Annualised damage cost has been presented in tables for four Max h values, which correspond to the estimated inundation level for a ~25year ARI, 100year ARI, 100year ARI + 0.9m levels, and 5000yr ARI (0.02%), with acknowledgement of increasing uncertainty with lower likelihood. The calculated annualised damage costs using the 5000yr ARI max h is referred to as “All WL” in the tables and the reporting (see example below for Bunbury). These levels have been set with the project team to demonstrate the financial risk to moderate, severe, and extreme events, with the difference between the ~100year ARI calculation and the "All WL" calculation providing an estimate of residual risk. No allowance for sea level rise is incorporated in the calculations. The range of inundation thresholds for the four levels and associated annualised damage values is indicated on the figure below.

Average Annual Damage		AEIP			
	WL	1.6m AHD	1.9m AHD	2.8m AHD	All WL
Area	ARI	~25yr	~100yr	~100yr +0.9m	
18.1: Preston River Region		$ 10K/yr	$ 30K/yr	$ 90K/yr	$ 100K/yr
18.2: Bunbury Townsite		$ 1.0M/yr	$ 4.0M/yr	$ 9.0M/yr	$ 10M/yr
Total Damage		**$ 1.0M/yr**	**$ 4.0M/yr**	**$ 9.1M/yr**	**$ 10M/yr**

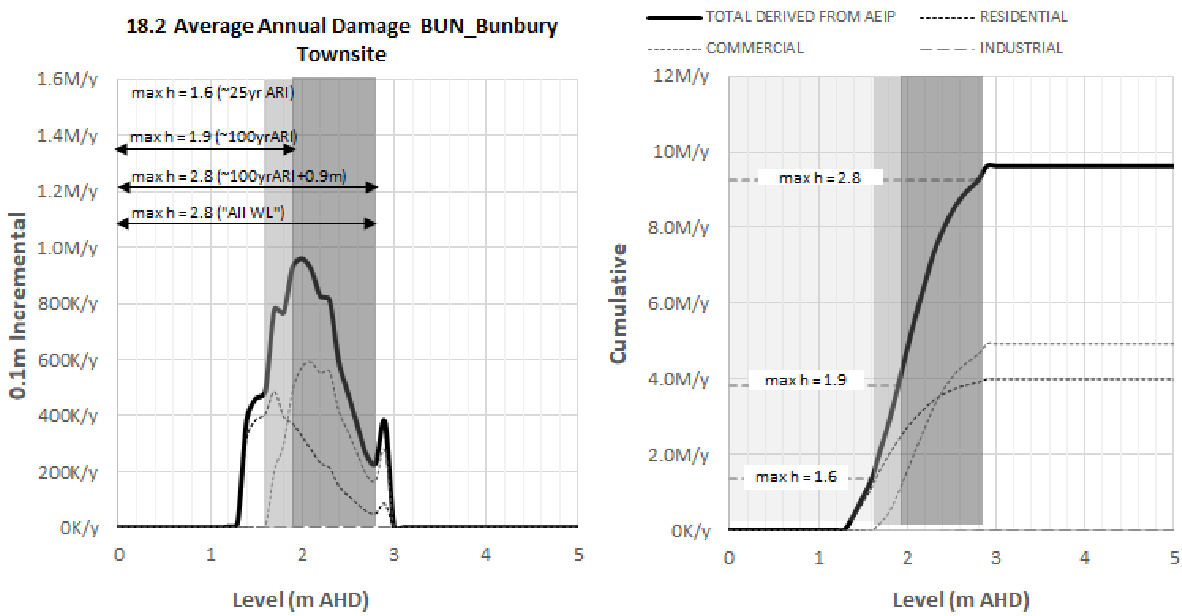

Figure 0-7: Average annual damage for Bunbury derived from AEIP values.

A Statewide Coastal Inundation Assessment for WA

APPENDIX C

SUPPLEMENTARY INFORMATION

Seashore Engineering

Department of Planning, Lands and Heritage
Department of Transport
GOVERNMENT OF WESTERN AUSTRALIA

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Appendix C: Supplementary Information

C1: Assessment Results: Asset Exposure

Inundation exposure of a range of key assets classes identified from AEIP assessment has been summarised at the 23 LGAs for the high (~25yr ARI), extreme (~100yr ARI) and "extreme +0.9m" scenarios. Overall, exposure is dominated by residential development, with a much smaller number of industrial and commercial building impacted.

Residential Buildings: Potential inundation of residential buildings was identified at 15 LGAs for the high scenario, increasing to 16 for the extreme and 21 for the "extreme +0.9m". Karratha and Northampton (Horrocks) had no exposure for the three scenarios.

The majority of the residential buildings impacted for the high and extreme scenarios were from two segments within the City of Busselton (Wonnerup, and Abbey-Geographe (Backwater)), with existing storm surge barrier protection considered ineffective to these levels in the percolation assessment. The Carnarvon Fascine segment had the 2nd highest number of buildings, which is associated with inundation into South Carnarvon via the Yacht Club, despite protection to a higher level provided by the South Carnarvon Surge Wall.

The number of residential buildings impacted increases significantly for the "extreme +0.9m", with Busselton and Bunbury (once storm surge barrier become ineffective) having high contribution. Notable increases also occur for Mandurah, Murray, Gingin (Lancelin) highlighting the sensitivity of these areas to exceptional inundation events and sea level rise.

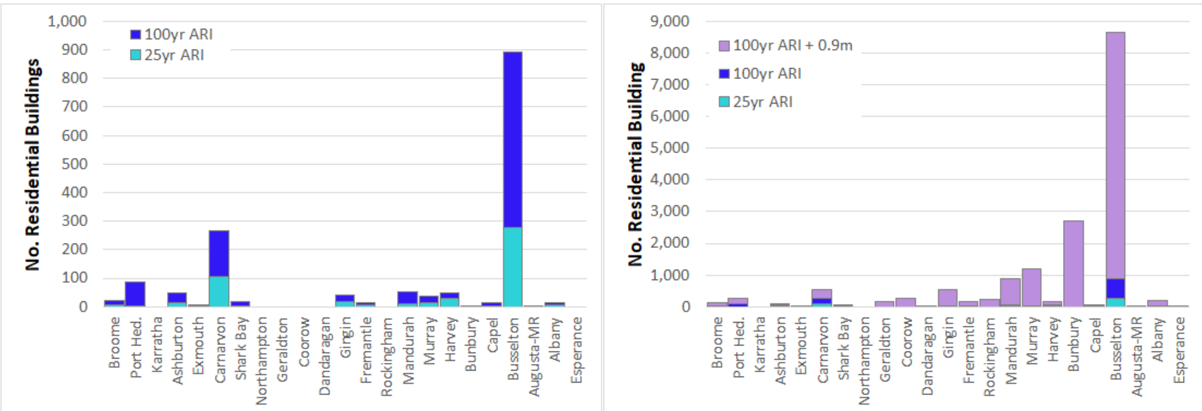
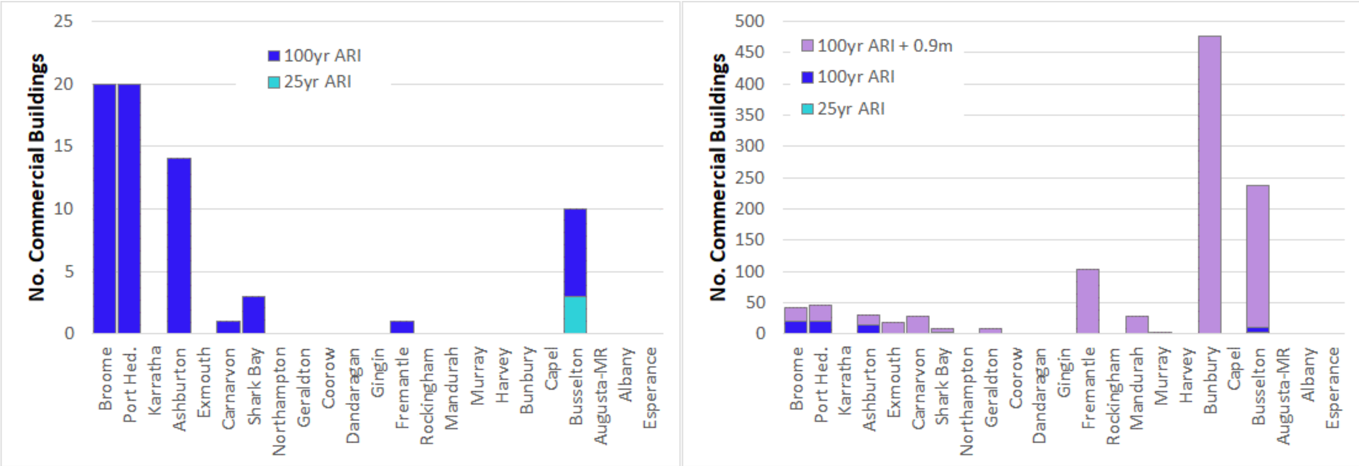


Figure 0-1: Geographic Distribution of Estimated Inundation Exposure of Residential Buildings Exposure of a significant number of residential buildings for the high (558) and extreme (927) scenarios at the Bunbury Townsite segment is mitigated by storm surge barrier protection.

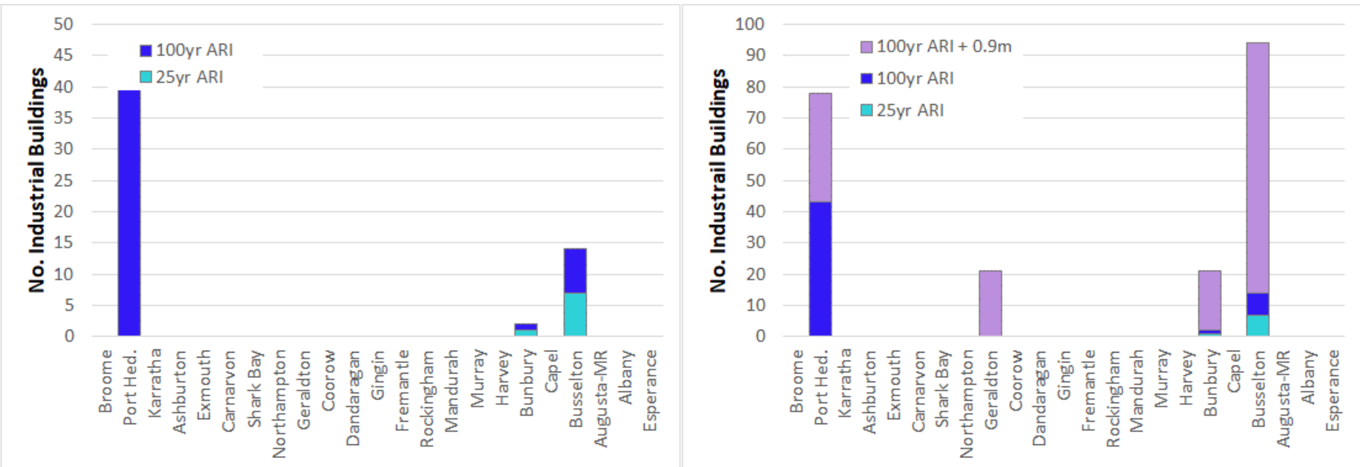
Commercial Buildings: Potential inundation of commercial buildings was identified at Busselton (Abbey-Geographe (Backwater)) for the high scenario, increasing to 7 for the extreme and 12 for the "extreme +0.9m". Notable contributions for the extreme scenario were from Broome, Port Hedland, Ashburton (Onslow) and Busselton, with substantial increases to the "extreme +0.9m" occurring from Fremantle, Bunbury (once storm surge barrier becomes ineffective) and Busselton.



Exposure of a significant number of commercial buildings at the high (71) and extreme (202) scenarios at the Bunbury Townsite segment is mitigated by storm surge barrier protection.
Figure 0-2: Geographic Distribution of Estimated Inundation Exposure of Commercial Buildings

Industrial Buildings: Potential inundation of industrial buildings was identified at four LGAs across the three scenarios, which were Port Hedland, Geraldton and Bunbury and Busselton. A large proportion of the buildings at Port Hedland, Geraldton and Bunbury are associated with their respective Port areas, while Busselton buildings are located within the Abbey-Geographe (Backwater) segment.

The two LGAs affected for the high scenario were Bunbury (Preston River) (1) and Busselton (7). Port Hedland becomes the third LGA and most impacted for the extreme scenario, while Busselton has the greatest increase for the “extreme +0.9m” scenario.



No industrial buildings are presently protected by the Bunbury storm surge barrier for the high and extreme scenarios at the Bunbury Townsite segment.
Figure 0-3: Geographic Distribution of Estimated Inundation Exposure of Industrial Buildings

Airports: There were no instances of inundation of major airport terminals captured in the AEIP assessment at the high, extreme and "extreme +0.9m" scenarios. However, potential inundation was identified within the following major airports or landing ground areas, with the following noted:

- **Karratha** – inundation encroaches on the eastern area boundary for the high scenario (+3.4m AHD), however the runway and terminal buildings are not impacted until >5.3m AHD, which is 0.2m above the "extreme + 0.9m" scenario.
- **Onslow** – inundation was identified for the high scenario (2.5m AHD), however construction of the airport occurred around 2015 and is understood to have incorporated fill for the runway and terminal. This fill was not incorporated in the assessment, as a 2010 lidar survey used predated the works. It is understood the runway and terminal buildings were set above 4.1m AHD, which is ~0.6m above the extreme scenario.
- **Carnarvon** – inundation encroaches on the airport area boundary from the south for the high scenarios (+1.7m AHD), with runway and terminal buildings not impact until +2.5m AHD, which is 0.4m above the extreme scenario.
- **Broome** – inundation encroaches on the airport area boundary from the east for the extreme scenario (+5.8m AHD), with inundation of the runway, airport buildings and terminal commencing at +6.0m AHD, 6.2m AHD and +7.85m AHD respectively.
- **Port Hedland** – inundation encroaches on the northern and eastern boundaries for the extreme scenario (5.0m AHD), with inundation of the runway and terminal commencing at +6.4m.
- **Leeman** – Western margin of the Landing Ground to the south of the townsite is impacted at +1.8m AHD, 0.6m above the extreme scenario

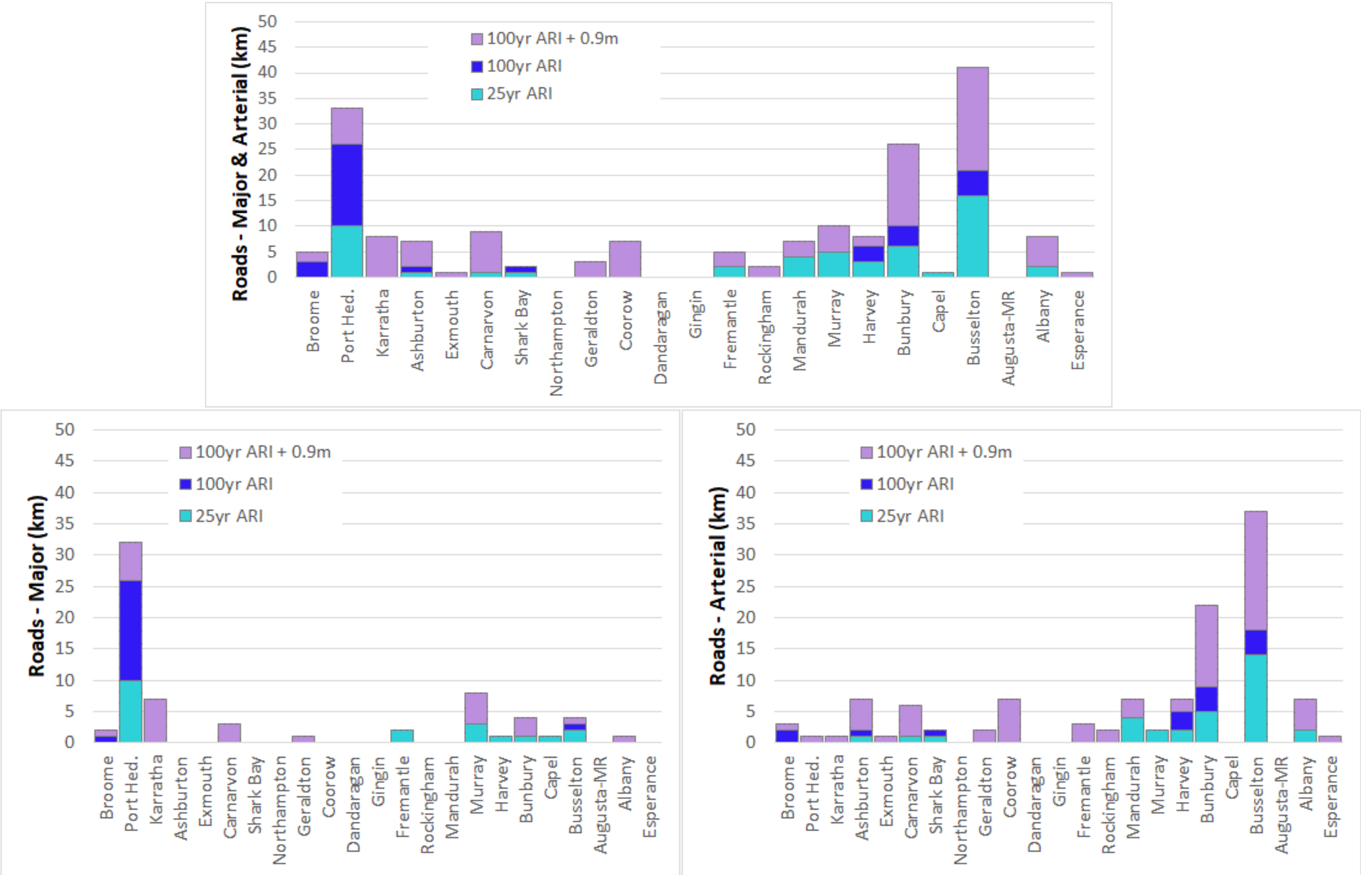
In summary, the **Broome, Carnarvon** and **Onslow** airports and Leeman Landing Ground have potential for inundation of airport assets for the "extreme +0.9m" scenario.

Roads: Roads are classified in AEIP as either major; or arterial or sub-arterial, with local roads not identified[1] and road definition potentially varying between locations. Consequently, comparison of the length of road identified from the assessment between sites has limited meaning, but can generally be related to inundation extents.

Potential inundation of roads was identified at 12 LGAs for the high scenario, increasing to 13 for the extreme and 19 for the "extreme + 0.9m". The LGAs with no road inundation for the three scenarios were Northampton, Dandaragan, Gingin, Augusta-Margaret River. However, it is acknowledged that Dandaragan and Augusta-Margaret River have local foreshore roads which are exposed, while road exposure can occur at Lancelin with dune breaching (Baird 2020).

Busselton, Bunbury and Port Hedland have the greatest road exposure to inundation across the three scenarios, with the Port Hedland network dominated by roads classified as major and Busselton and Bunbury consisting mainly of arterial and sub-arterial roads. At a level below, Mandurah, Murray, Harvey and Albany have relatively high exposure for the high scenario. It is acknowledged that in some instances bridge crossings over water bodies are included in exposure.

[1] **At Augusta** – the first impact on road from AEIP was incurred +3.2m AHD, which is when inundation crosses Blackwood Ave. It is acknowledged that several local roads fronting Blackwood Ave are impacted at lower levels commencing around the extreme scenario of +1.7m AHD.



Roads are presently protected by the Bunbury storm surge barrier for the high and extreme scenarios at the Bunbury Townsite segment.

Figure 0-4: Geographic Distribution of Estimated Inundation Exposure of Roads

Railway: Potential inundation of railway tracks was identified 4 LGAs at the high and extreme scenarios, which increased to 6 LGAs at "extreme +0.9m". Two of these sites are apparently associated with bridge crossings over water bodies (e.g. One Mile Jetty at Carnarvon; Fremantle Railway Bridge). There were no impacts to railway stations.

The majority of the railway tracks were located at Port Hedland which has a dense rail network to support industry. Bunbury, Geraldton and Esperance include railway servicing Ports, with the only public railway impacted at Fremantle for the "extreme + 0.9m" scenario.

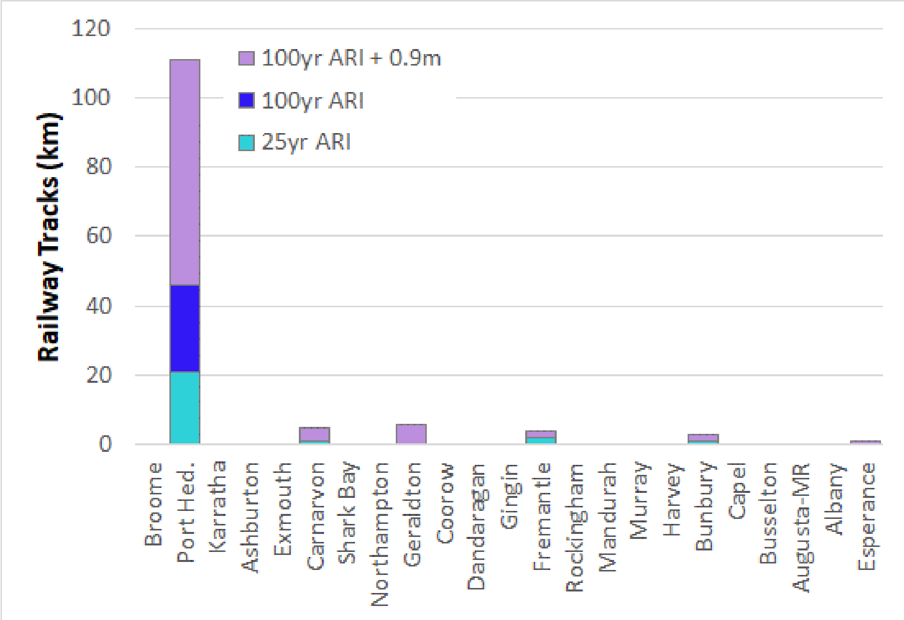


Figure 0-5: Geographic Distribution of Estimated Inundation Exposure of Railway

Schools: The only school impacted at the extreme scenario was at Carnarvon (+2.1m AHD), which is assumed to be the Carnarvon School of the Air within the Carnarvon Fascine segment. Review of levels adjacent to the building suggests that inundation of its buildings commences just above this level, at +2.3m AHD. It is acknowledged that the Lancelin Primary School sits partly below the extreme scenario (+1.2m AHD), but inundation requires breaching of the dune system during an extreme event (Baird 2020). For the “extreme +0.9m” scenario, schools are affected at Onslow (1), Carnarvon (3), Murray (1), Bunbury (4).

Wastewater: Three wastewater management or treatment plants were identified at Port Hedland, which includes:

- A wastewater management site located on Cooke Point Road for the high scenario. This facility was built after the 2010 lidar used in the assessment, and therefore land modification for inundation mitigation was not incorporated.
- A wastewater treatment plant for the extreme scenario, which is likely a BHP facility at Nelson Point.
- A wastewater management site for the “extreme +0.9m” scenario, which is the facility on Schillaman Street, in Wedgefield.

For the “extreme +0.9m” scenario, additional facilities are also impacted at Exmouth, Carnarvon, Rockingham and Mandurah.

Other:

- A single power station was identified for the extreme scenario (+2.1m AHD) within the Carnarvon Fascine segment. This is apparently located on Cornish St, East Carnarvon, with inundation commencing around +1.9m AHD.
- Ambulance stations were identified at Onslow, Leeman, Bunbury and Busselton for the “extreme +0.9m” scenario.
- A single retirement home in Bunbury is affected for the extreme scenario, with nursing or retirement homes affected for “extreme + 0.9m” at Onslow (1), Busselton (5).

Appendix C2: Event Damage Estimates Per LGA ($ AUD)

LGA	High (~25yr ARI)	Extreme (~100yr ARI)	~500yr ARI	Extreme +0.9m (~100yr ARI+0.9m)	~500yr ARI + 0.9m
Broome	$66,000	$620,000	$6,700,000	$34,000,000	$97,800,000
Port Hed.	$77,000	$1,400,000	$20,600,000	$82,200,000	$253,800,000
Karratha					
Ashburton	$360,000	$3,200,000	$13,400,000	$33,600,000	$69,700,000
Exmouth		$120,000	$370,000	$1,300,000	$12,500,000
Carnarvon	$2,300,000	$9,900,000	$23,700,000	$51,200,000	$87,000,000
Shark Bay		$650,000	$2,300,000	$7,000,000	$14,500,000
Northampton					
Geraldton					$120,000
Coorow					
Dandaragan					$140,000
Gingin			$420,000	$1,200,000	$2,500,000
Fremantle		$190,000	$500,000	$1,600,000	$6,600,000
Rockingham					
Mandurah	$57,000	$390,000	$1,900,000	$4,000,000	$7,500,000
Murray		$370,000	$940,000	$1,800,000	$1,800,000
Harvey	$780,000	$2,700,000	$4,000,000	$7,200,000	$11,900,000
Bunbury	$120,000	$800,000	$1,200,000	$348,200,000	$617,500,000
Capel	$170,000	$230,000	$260,000	$1,100,000	$2,200,000
Busselton	$20,600,000	$40,600,000	$55,700,000	$119,700,000	$319,300,000
Augusta-MR				$46,000	$110,000
Albany	$180,000	$180,000	$500,000	$500,000	$1,000,000
Esperance					
Total with Bunbury Storm Surge Barrier	**$24,600,000**	**$132,600,000**	**$1,506,000,000**	**$4,085,600,000.00**	**$7,326,500,000.00**
Total Without Storm Surge Barrier	**$48,300,000**	**$288,300,000**	**$1,506,000,000**	**$4,085,600,000.00**	**$7,326,500,000.00**

Appendix C3: Average Annual Damage Estimates per LGA ($ AUD)

LGA	≤High	≤Extreme	≤Extreme + 0.9m	All
Broome	$1,000	$31,000	$314,000	$692,000
Port Hedland	$1,000	$100,000	$498,000	$1,956,000
Karratha	-	-	-	$5,000
Ashburton	-	-	$188,000	$511,000
Exmouth	-	$4,000	$15,000	$131,000
Carnarvon	$43,000	$375,000	$906,000	$1,159,000
Shark Bay	-	$24,000	$104,000	$145,000
Northampton	-	-	-	-
Geraldton	-	-	$16,000	$25,000
Coorow	-	-	-	-
Dandaragan	-	-	$127,000	$129,000
Gingin	-	-	$35,000	$35,000
Fremantle	-	$7,000	$106,000	$106,000
Rockingham	-	-	$4,000	$4,000
Mandurah	$6,000	$39,000	$132,000	$132,000
Murray	-	$27,000	$53,000	$53,000
Harvey	$49,000	$122,000	$232,000	$239,000
Bunbury	$13,000	$34,000	$2,330,000	$2,716,000
Capel	$47,000	$55,000	$76,000	$77,000
Busselton	$1,815,000	$3,023,000	$5,938,000	$6,311,000
Augusta-Margaret River	-	-	$11,000	$14,000
Albany	$25,000	$34,000	$41,000	$41,000
Esperance	-	-	-	-
Total	**$2,002,000**	**$3,917,000**	**$11,122,000**	**$14,480,000**
Bunbury without storm surge barrier	**$1,358,000**	**$3,846,000**	**$9,330,000**	**$9,716,000**
Busselton without storm surge barriers	**$4,415,000**	**$5,623,000**	**$8,538,000**	**$8,911,000**
Total without storm surge barriers	**$5,946,000**	**$10,329,000**	**$20,722,000**	**$24,080,000**