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Coastal Inundation Hazard Assessment in Australian Tropical Cyclone Prone Regions

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Abstract: One of the hazards associated with tropical cyclones (TCs) is a storm surge, which leads to coastal inundation and often results in loss of life and damage to infrastructure. In this study, we used GIS-based bathtub models and tide-gauge-derived water levels to assess coastal inundation scenarios for the landfall region of TC Debbie. The three scenarios modelled what could have happened if the TC's maximum storm surge had coincided with the maximum storm tide for that day, month, or TC season, where the water levels were determined through analysis of tide gauge data, using a new method called the variable enhanced Bathtub Model. Additionally, this study analysed the impact of excluding the correction of water levels with the Australian Height Datum. Our study found that between the least and most severe scenarios, with the input water-level difference for the model along the coastline being 0.43 m, the observed inundation depth of the analysed populated region increased from 0.25 m to 1 m. Ultimately, it was found that in the worst-case scenario, the study region could have experienced coastal inundation 0.63 m higher than it did, inundating 72.53 km^2 of the coast. The results of this study support the consensus that coastal inundation is highly dependent on the characteristics of the terrain, and that coastal inundation modelling, such as that completed in this study, needs to be performed to better inform decision makers and communities of the potential impacts of TC-induced storm surges.

Keywords: tropical cyclones; storm surge; coastal inundation; hazards assessment; Australia

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1. Introduction

Coastal inundation refers to flooding that occurs due to a rise in sea level, which causes seawater to move inland of the coast. Coastal inundation is one of the main risks for coastal regions worldwide; its main cause being storm surges, a hazard often associated with tropical cyclone (TC) events [1–4]. TC-prone regions of Australia have experienced some of the most extreme TC events in the country [1], with coastal inundation being one of the main contributors to the damage and losses caused by flooding [5]. In the event of a TC, these elevated water levels can last several hours before and after TC landfall; however, the storm surge magnitude is mostly dependent on wind speeds [6], which are influenced by TC characteristics such as their intensity, speed, and structure [1].

TCs can result in loss of human lives and extensive damage to infrastructure [7,8]. Worldwide, more than 418,000 lives have been lost as a result of TC disasters between 1979 and 2016 [9]. With global warming, overall numbers of TCs are projected to decrease globally; however, the proportion of the most intense TCs is projected to increase [10]. Historical records indicate that the Australian region experiences on average eleven TC events a year, with four to five making landfall [11,12]. These typically occur during the TC season, which in the Southern Hemisphere usually lasts for six months from November to

April [7,12]. Coastal communities in Australian TC-prone regions that are at risk from TCs and associated storm surge hazards require appropriate risk assessments [13].

Risk assessments are increasingly necessary to enable communities to determine potential impacts on human activities, infrastructure, and natural resources from hazardous events [8]. They also aid decision makers in making evidence-based decisions in anticipation of and in response to hazards [14]. Whilst nation-wide TC risk assessments for Australia have been developed [7,8,15,16], there is increasing support for smaller-scale Local Government Area (LGA) assessments, which are more affordable and community-specific and unique to the smallest government decision-making bodies and associated with higher accuracy [8,17].

Developing an assessment focusing on one hazard associated with TCs is a standard approach, including but not limited to assessments on TC-induced wind [18], rainfall [19], and storm surges [20]. According to Garcia and Fearnley [21], risk maps for individual hazards can foster transparent communication by authority figures. As individual hazards can impact communities and environments differently, the maps of individual hazards in addition to singular multi-hazard assessment are beneficial to the public's understanding and acceptance of the risks due to the hazards. Due to storm surges being one of the most dangerous hazards associated with TCs [7], this study will primarily develop a hazard assessment of TC-induced storm surges. Such hazard assessments are typically completed using computational models to estimate coastal inundation extents.

Modelling TC-induced coastal inundation can be achieved using various coastal modelling software, e.g., simple bathtub models (sBTMs), hydrodynamic models, and enhanced bathtub models (eBTMs). Quantifications of storm surge hazards often involve the use of advanced modelling software, running calculations that usually require vast quantities of fine-resolution data, such as bathymetry, topography, and sea-level records, which can be computationally expensive to run. Resolution is a significant factor in risk assessments as information with the greatest detail is a priority for coastal planning stakeholders [22].

sBTMs are the simplest form of coastal inundation modelling and are commonly only referred to as "bathtub models"; however, their distinction in this study is important, to separate them from eBTMs. The sBTM produces an inundation map, whereby areas lower in elevation than a defined water-level scenario are assumed to be inundated, producing a binary output of "flooded" or "unflooded" areas [23]. Through this, it provides very basic coastal inundation extents, and it can be applied almost anywhere, as it only requires the proposed water level to be investigated, and elevation data. However, some sBTMs are found to be too rudimentary; they do not incorporate uncertainties inherent to spatial data and modelling [24]. They are considered inappropriate to inform local governments and risk organisations for risk assessments due to their extent of overestimation [25]. As a result, sBTMs are regarded only as intermediate tools for assessing coastal inundation extent and will therefore only serve as a point of comparison for this study's application of the eBTM.

Hydrodynamic models are in direct contrast to sBTMs and address most of their shortcomings, typically involving complex physics and mathematics to simulate potential surge heights based on model parameters and inputs [26,27]. While the sBTM only produces a binary output of "flooded" or "unflooded" states, hydrodynamic models can provide the depths and extents of coastal inundation at high resolutions. Despite their reputability, it is impractical to apply hydrodynamic models worldwide at this stage as they require immense amounts of high-resolution data, computationally expensive resources, and highly specialised climate modelling experts. Hydrodynamic modelling is a very expensive and inaccessible tool for local regions in need of the information they provide.

In an effort to address the shortfalls of the sBTM and hydrodynamic models, the static eBTM was developed in 2020, by Williams and Lück-Vogel [28]. It was found in consultations with experts in operational modelling that Geographic Information System (GIS) is the most accessible technology, used by 90% of the respondents, compared to only

27% of those who indicated that hydrodynamic modelling skills were available within their organisations [29]. Additionally, their model directly considers beach slope, surface roughness, and the coastline shape, as well as the standard elevation and chosen water-level data. Despite the emphasis that the eBTM cannot replace hydrodynamic models, it does present as the best intermediate method between the sBTM and hydrodynamic models, allowing regions to be better informed of their potential coastal inundation extents until a robust hydrodynamic model can be run.

Our study is an extension of the original study, featuring the first application of the variable eBTM. Originally, Williams and Lück-Vogel's [28] study only featured the static eBTM, which assigns one Roughness Coefficient (RC) value to the entire study area; however, in their development of the static eBTM, they also developed the variable eBTM used in this research. This study features an input of RC values unique to the terrain of the TC Debbie study area at a 1-m resolution, thus providing more detail than a static value. Additionally, the results of this research inform the coastal inundation of a study area 67 times larger.

Validating any climate model with observational data is always essential; however, it is a common limitation in storm surge studies, especially in analyses investigating TC-induced coastal inundation. Coastal inundation data are primarily achieved through analysis of satellite data; however, due to the nature of TCs causing extensive cloud cover around the affected regions, this is not feasible for most techniques [30,31]. As a result, validation of the model presents as a limitation in this study, as well as many other studies of a similar nature. The primary implications for the lack of validation data, mean that estimations of coastal inundation cannot be assessed for their accuracy, and this, thus, also reduces the feasibility of iterating methods being able to increase accuracy and improve models.

This study defines coastal inundation scenarios as different circumstances of a past TC event. TC Debbie (2017) was one of the most damaging TCs that has made landfall in Australia; however, the coastal inundation experienced was considered a "near-miss" and could have been 18% higher as estimated by [32]. As the TC's maximum storm surge of 0.99 m did not occur simultaneously with the highest astronomical tide of 5.93 m by five hours, the actual event could therefore have experienced much more severe coastal inundation if the two phenomena had coincided. Based on this idea, this study aims to investigate what impact TC Debbie could have had under these more adverse tide scenarios.

For the coastline of TC-prone Australian regions, the TC season largely drives the extreme variations in sea level [33,34]; however, the monthly variability of extreme sea levels is also closely linked to monthly tide height variability [35]. Consequently, this study will consider: What would have happened if TC Debbie had coincided with the highest tide of the day, highest tide of the month, and highest tide of the TC season, with unique inundation maps produced for each scenario.

Similar studies quantifying coastal inundation risk have been undertaken for coastal inundation in Australia. McInnes et al. [36] and Hanslow et al. [37] completed studies assessing the current and future vulnerability and exposure of coastal inundation in Australia's southeast, with a particular focus on estuarine locations. These earlier studies both considered storm surges and used similar tidal data to this study; however, their focus was on sea-level extremes more broadly, whilst this study investigated TC-induced storm surges specifically. These two studies also defined possible coastal inundation scenarios as "1-in-100-year events", which could be ambiguous to stakeholders using the information. As a result, this study considers hypothetical "worst-case scenarios" grounded in reality, as it considers a specific TC event, and analyses what did happen during the event and compares it to what could have happened if some conditions were more severe.

Additionally, coastal inundation and even sea-level rise research often ignore the role of the Australian Height Datum (AHD). The AHD is Australia's official datum to which all vertical controls for mapping are to be referred [38], and studies often fail to correct water-level values against the national "0-m" water level and elevation, which is also calibrated against the AHD. As this study will also be defining its water levels based on tide gauge data, being sensitive to the AHD is essential for an accurate value determination and, thus, model output and analysis; such water levels that account for AHD values will, for the purposes of this study, be referred to as "AHD-corrected" water levels. AHD values are defined in this study as the difference in height between a tide gauge's "0 m" and the AHD's zero, as shown in Figure 1.

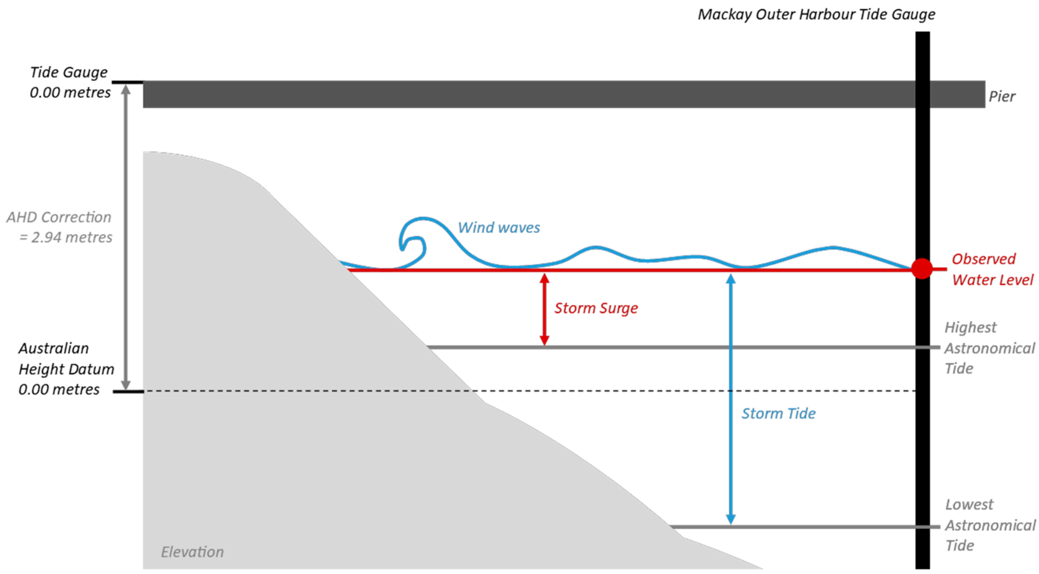

Figure 1. The total observed water level at the coastline in the event of TC primarily results from the summation of storm surge and astronomical tide, forming a storm tide. The relationship between the Mackay Outer Harbour tide gauge, the water levels it records, its relation to the 0.00 m of the Australian Height Datum, and 0.00 m of the tide gauge.

The overall aim of this research is to model potential 'worst-case scenarios' grounded in reality for TC Debbie's coastal inundation extent, whilst also comparing three GIS-based models, the sBTM, static eBTM, and the novel variable eBTM, and assessing the impact of correcting for AHD values. This will primarily be achieved by running hypothetical scenarios where the maximum storm surge observed in the event coincided with higher astronomical tides within the same TC season. It is hypothesised that the variable eBTM would be most preferable, as it is an extension and more detailed application of the static eBTM, which is already a proven improvement on the sBTM. It is also hypothesised that not directly considering and defining AHD water-level corrections severely overestimates predictions of coastal inundation extent. The objectives of this study are as follows:

I. Identify the preferred GIS-based model for predicting coastal inundation extents through a case study on TC Debbie's affected region of Mackay. This objective decides which model is then utilised for the remainder of the study's analyses.
II. Evaluate three hypothetical worst-case scenarios for the TC Debbie event for the affected region of Mackay by first defining the water levels to represent the scenarios. These will be defined as the addition of the highest observed storm surge during the event plus the highest astronomical tide observed in TC Debbie's landfalling: day, month, and TC season.
III. Compare the differences between the results of the AHD-corrected and uncorrected conditions by removing the AHD corrections from water-level scenarios and running these uncorrected values through the model.

As a result, this study will support hazard risk reduction efforts by establishing a method that supports informing the relevant communities and governments of the potential extent of coastal inundation in the event of another TC like TC Debbie.

2. Materials and Methods

Figure 2 briefly outlines this study's overall methodology. In order for the objectives of this study to be complete, step 3 of Figure 2, steps 1 and 2 must first be accomplished. Sections 2.2–2.6 will explain how each of the inputs for the models were produced and the sources of the data, whereas Section 2.1 will discuss the models used in this study more explicitly.

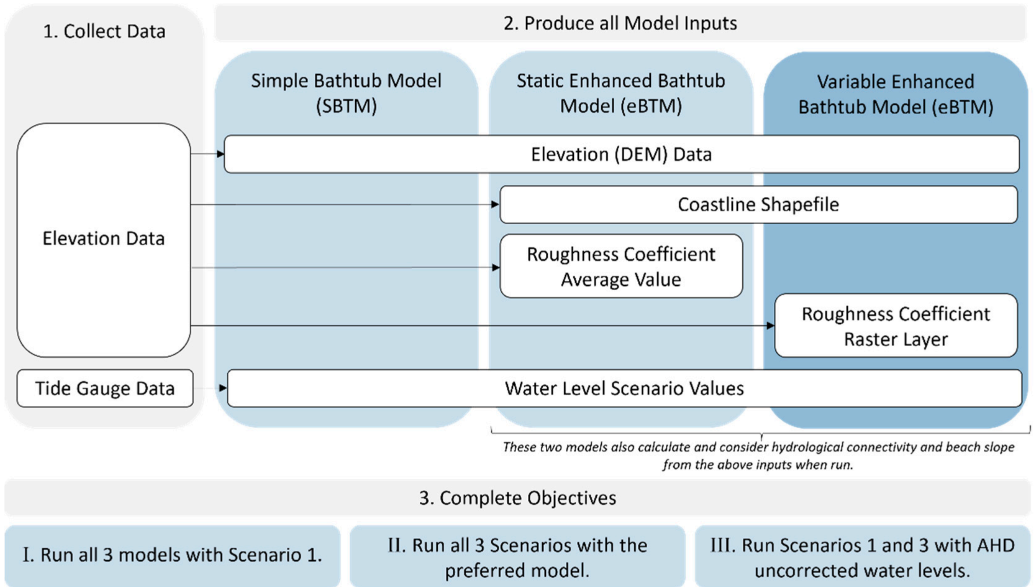

Figure 2. A summary of the methodology, highlighting the differences between the individual methodologies of the three models compared in this study.

2.1. Model Methodologies

Our objective was to compare the three models against each other, to confirm the hypothesis that the variable eBTM is the preferable model of the three available GIS bathtub models. To the best of our knowledge, this study is the first application of the variable eBTM to date. This model is the developer's extension of the static eBTM, a model developed in Williams and Lück-Vogel's [28] study. The extension features a change in the resolution of one variable, whereas, in the original conception (the static eBTM), the RC could only be one constant value for the entire study area. In the extension, this variable can be increased to the highest resolution possible for the data available. In this study, this was a resolution of 1 m.

Beyond the unique RC inputs, the static and the variable eBTM also use elevation, a specified water level, and a clearly defined coastline to run the model. Though not directly input into the model, the models also use the data provided to calculate and consider the hydrological connectivity and beach slope of the study area. Further detail on the methodology of the eBTMs can be found in their original findings [28].

The foundation of Williams and Lück-Vogel's [28] study was to compare the results of their then-novel static eBTM results to the results produced by the sBTM, a model well established across the inundation community. As a result, this study ran a similar approach by running both the sBTM and the static eBTM, to be a point of comparison for the novel variable eBTM. In their Cape Town study, Williams and Lück-Vogel [28] compared the performance of the sBTM and the static eBTM for all scenarios, and their results indicated that as the scenarios were more extreme, the greater the overestimation from the sBTM.

The biggest difference between the eBTMs and the sBTM is that the eBTMs estimate the extent and the depth of inundation of the modelled flood event. However, the sBTM can only state if it predicts an area to be "flooded" or "unflooded", with no ability to distinguish the severity of the flooding it predicts. This is driven by the significant difference in their methodologies. The eBTMs consider a number of variables, as explained above, the sBTM only considers the required two inputs, the elevation of the study area of interest and the specified water level. Furthermore, the sBTM determines flooded and unflooded regions extremely simplistically, where any point of elevation that is lower than the specified water level is considered "flooded". Details on the exact parameters and function of the sBTM methodology can also be found in Williams and Lück-Vogel's study [28].

2.2. Study Area

TC Debbie made landfall on Airlie Beach on 28 March 2017 at 12:40 p.m. [39]. This severe TC caused fourteen deaths and up to AUD 3.5 billion in damage [40], which was mostly attributable to flooding. Whilst it is ranked as the most dangerous TC to impact the Australian region since 1974's TC Tracy [41], the event's coastal flooding is considered a "near-miss" for the landfall region [32]. This is because TC Debbie's maximum storm surge did not coincide with the region's high tide, meaning the observed impact of TC Debbie was not its worst-case scenario.

The study area constitutes one of the main coastal population centres impacted by the landfall of TC Debbie, the Mackay region, as presented in Figure 3. Although TC Debbie made landfall north of Mackay, this region was still significantly impacted by storm surge and flooding, experiencing multiple evacuations, power outages, and port closures because of the TC [40]. A focus on modelling coastal inundation for Mackay is further supported by a multi-hazard risk assessment which identified the Mackay LGA as having the highest storm surge hazard [42]. The study area has an area of 365 km^2 and features one tide gauge, also shown in Figure 3.

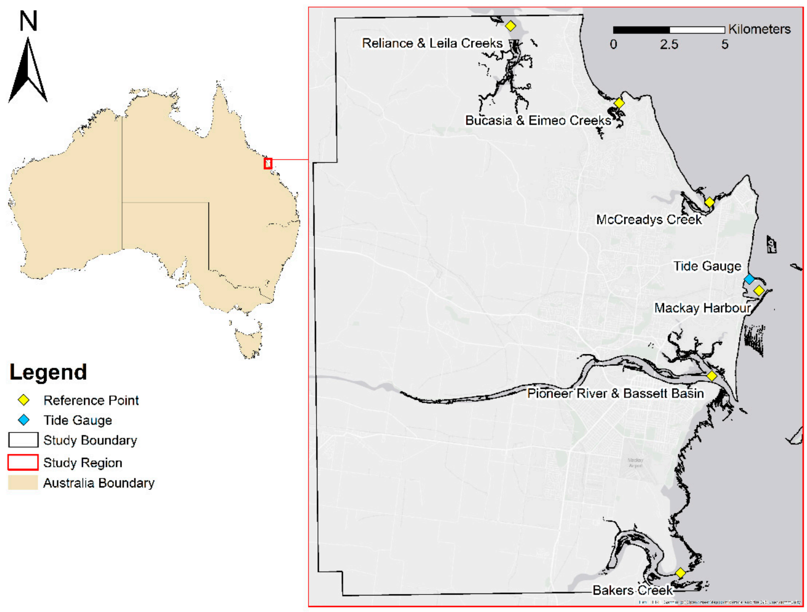

Figure 3. Study region of Mackay along coastal Queensland, Australia.

Bordering the study region on the east is the Coral Sea, the region contains numerous unique coastline features. From north to south, the study area contains Reliance and Leila Creeks, Bucasia and Eimeo Creeks, McCready's Creek, Mackay Harbour, the Pioneer River, Bassett Basin, and Bakers Creek (Figure 3). The region also contains smaller water body features such as lagoons and lakes; however, they are not considered in this study. Due to the nature of this section of the Queensland coastline, particularly its exposure to the Coral Sea, Mackay also has a macro-tidal range, meaning the tide is highly variable with respect to time. This behaviour makes inundation modelling and storm tide forecasting for the region difficult in identifying the water level of interest or in the timing of landfall, even by just a few hours, as it can translate to hundreds of metres of difference in the position of the waterline [32].

2.3. Input Data

The main input parameter for any accurate coastal inundation model is high-resolution topographic data on the area of interest as they provide the most accurate and useful information [26,43]. This study will be using topographic LiDAR-derived Digital Elevation Model (DEM) data as LiDAR is strongly suited to assessments with elevated water levels, attributed to its low vertical error [44], as shown in Figure 4, sourced from [45]. It has an average density of 2 points per square metre [45] for all models and scenarios. The 1-m resolution data had a projection of Geocentric Datum of Australia 1994 Map Grid of Australia Zone 55, which has a longitude of 144° E to 150° E, through the Queensland Government's LiDAR Data projects [45]. The vertical datum used was the AHD, Australia's official datum to which all vertical control for mapping is to be referred [38]. This datum is assigned a value of 0.00 m, (0.00 m AHD-corrected), as the mean sea level for 1966–1968 [38]. It is important to note that the mean sea-level value should be calculated from 19-year-long continuous records of water levels [46], presenting a limitation to the accuracy of the Australian datum as this was only calculated over three years.

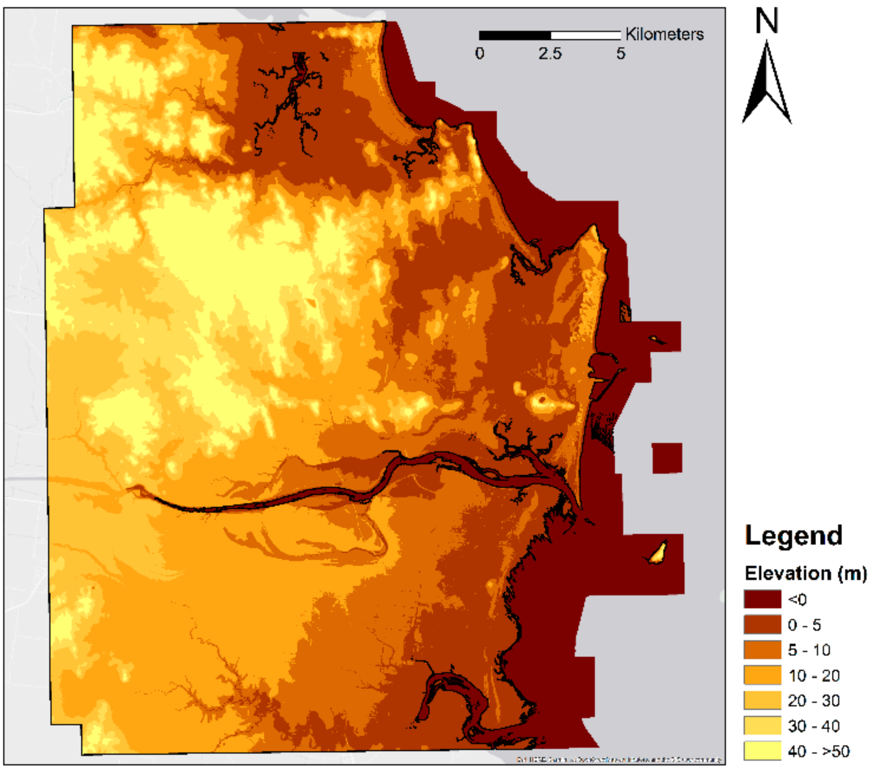

Figure 4. Map of the Mackay study regions available 1 m resolution elevation data (metres).

The eBTM requires a starting point for the inland inundation to be modelled. For coastal inundation specifically, this would be the coastline. A coastline was extracted from the LiDAR-derived DEM data as the zero-elevation contour line in a polyline shape file format in ArcMap 10.8.1, a replication of Williams and Lück-Vogel's [28] method applied to their Cape Town study using the static eBTM. The final coastline used to input into models is shown in Figure 3.

The static eBTMs require a single surface RC value whilst the variable eBTM uses a raster layer of these values as an input. For the model, the RC is defined as being between 0 and 1, where it is the degree of irregularity of a surface. In the receiving environment of water, a small RC (0) represents a region with a gentle slope and smooth surface that allows for unrestricted movement of water, and vice versa for a large RC (1) [47]. This study included the development of an RC raster layer, as shown in Figure 5, through QGIS 3.30 with the roughness tool in the Geospatial Data Abstraction Analysis Library (GDAL). This tool calculates an RC through the largest inter-cell difference between a central pixel and its surrounding cells. From this initial roughness raster layer, it was then linearly normalised to fit the model's RC definition [48]. For the static eBTM, its RC was defined as the average of the raster data, a value of 0.01, and for the variable eBTM, the RC raster layer was used.

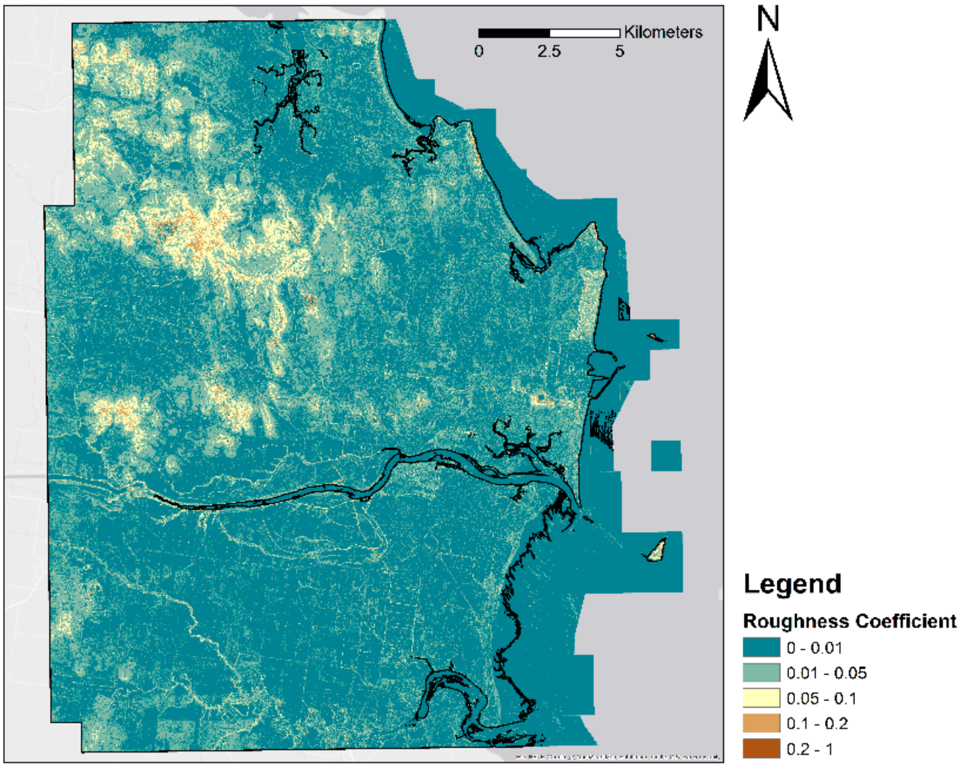

Figure 5. The linearly normalised RC data produced by QGIS 3.30. The bluer the area, the lower the RC, and the smoother the terrain, and thus the easier it is for water to move.

2.4. Define Water Levels

In this study, observations and tide-level data were obtained from the Mackay Outer Harbour tide gauge with water-level recordings every 10 min, which is positioned at 2.94 m AHD and with its location shown in Figure 3. To define these water levels, the tide gauge's tide and observed data were sourced from the Queensland Government's Open Data Portal [49], detailed in Appendix A. For this study, the tide data will be defined as Mackay's astronomical tide data and the observed data defined as the recordings of observed sea levels from Mackay's tide gauge. A residual value for this data has also been calculated, defined as the difference between the tide and observed water levels at a point in time [32]. This value represents our storm surge values.

From these values, further data analysis was completed to determine the storm surge height and the water levels for three hypothetical scenarios considered in this study. The AHD value is also considered for all finalised water levels and was controlled for in the calculation of the water level in the last step, to minimise potential errors. This was achieved by taking away the tide gauge's AHD value of 2.94 m from the defined water levels.

The highest observed water level on 28 March 2017, the day of landfall, at the Mackay Outer Harbour tide gauge was recorded as 3.34 m AHD-corrected at 10:50, as shown in Figure 6a. This value will be referred to in this study; however, it was beyond the scope and timeline of this study to consider this water level as its own scenario. In Figure 6b, the residuals are also plotted, and they show that the maximum observed surge for the day was 0.99 m at 05:40 28 March 2017. This indicates that for TC Debbie, the maximum surge and tide missed coinciding by approximately five hours in Mackay.

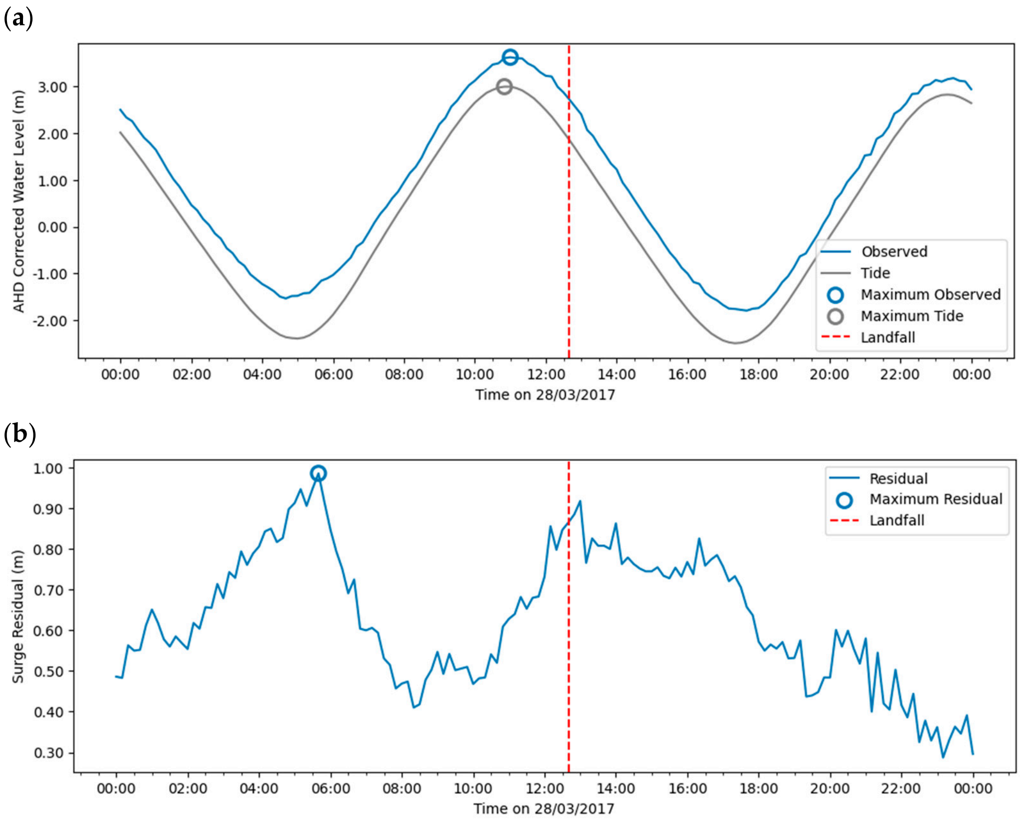

Figure 6. AHD-corrected water levels (**a**) and surge residuals (**b**) recorded at the Mackay Outer Harbour tide gauge on 28 March 2017 in Australian Eastern Standard Time (AEST, UTC + 10 h). The red vertical line shows 12:40, the approximate landfall time of TC Debbie at Airlie Beach.

The maximum storm surge value for this study is considered to be the maximum residual for the day of landfall, which for TC Debbie was 0.99 m on 28 March 2017 and is shown in Figure 6b. This value is interpreted as the highest observed storm surge on the day of landfall and will be included in all future calculations of scenario water levels. Mortlock et al.'s [32] study also calculated the storm surge values for TC Debbie, with a near-identical method. However, as their period of interest was from 27 March 2017 to 30 March 2017, whilst this study only looked at the day of landfall, their maximum storm surge value was 1.12 m for Mackay.

The scenarios analysed in this study were based on selecting three time frames that represented the scenarios to be investigated, finding the highest observed water levels during this time frame from the data, adding it to the storm surge height calculated in Section 2.4 and taking away the AHD-corrected value. The three chosen scenarios represent the water levels expected if the maximum storm surge had coincided with the highest water level on the day of landfall (Scenario 1), the highest water level on the month of landfall (Scenario 2), and the highest water level of the TC season (Scenario 3). The final values of these water-level calculations are presented in Table 1.

In this study, AHD-uncorrected water levels were also run in the model, to compare to the outputs produced by the corrected water levels and to assess the impact of utilising inaccurate water levels. The AHD-uncorrected water levels were established by removing the AHD correction, so the final AHD-uncorrected water level was the sum of the maximum water level for the specified time period plus the storm surge value.

Table 1. Summary of scenario water-level values.

Scenario	Scenario Description	Start Date	End Date	Tide Record Date and Time (24 h)	AHD-Corrected Water Level (m)	AHD-Uncorrected Water Level (m)
1	Day of landfall	28 March 2017	28 March 2017	28 March 2017 10:50	3.97	6.91
2	Month of landfall	1 March 2017	31 March 2017	10 March 2017 9:40	4.10	-
3	TC Season of landfall	1 November 2016	30 April 2017	12 January 2017 10:40	4.43	7.37

Scenarios 1 and 3 were selected for the AHD correction analysis, with the values specified in Table 1. Their respective water levels are the lowest and highest in this study, thus representing the lower and upper bounds of the impact of not correcting the AHD values. It is important to note that this impact is specific to the Mackay region, where the tide gauge's location is 2.94 m above 0 m AHD; all tide gauges will have a unique difference between their 0 m and the corresponding AHD 0 m. As a result, the results shown only serve to highlight the impact of misinterpreting AHD values and are results that are not directly applicable to other locations with dissimilar differences in their elevation, or with their AHD correction values. It must also be noted that an AHD correction of 2.94 m is large, so this study on Mackay highlights an extreme case.

Whilst there are other "maximum tide" values that could be used to establish the water levels for other scenarios, such as annual maximums, they would not be directly applicable to this study. The main premise of this study is to assess the hazard of TC-induced coastal inundation. Hence, all established scenarios must correspond with as similar conditions as possible to the event in question. As a result, the only feasible period to explore different theoretical water-level scenarios for TC Debbie is during the same TC season in which it occurred.

2.5. Model Runs

Objective I of comparing the models featured one run each for the sBTM, the static eBTM, and the variable eBTM with Scenario 1, an AHD-corrected scenario, which represents the highest water level that theoretically could have occurred on the day of landfall. By keeping the scenario (water level) for the model comparison constant, it minimised the risk of misinterpreting differences between the models to differences in the scenarios. As the scenario is the same for all models in the comparison, any differences observed between the outputs of each model are purely differences in the models and the inputs they permit.

For the purpose of this study, it is assumed that the model with the highest resolution data will be the best-performing model. This is driven by the consensus that hydrodynamic models perform coastal inundation models most accurately, due to their ability to utilise data and perform calculations at an even higher resolution than any of the bathtub models can perform. Thus, the more a GIS model can perform like a hydrodynamic model, the more suitable it must be for coastal inundation modelling.

As explained in the Materials and Methods section, the variable eBTM objectively fits the description of being the highest resolution of the three models, as it features a 1-m resolution RC layer as an input whilst the static eBTM only allows one static value for the whole study area. Consequently, the variable eBTM was the model selected to run the three AHD-corrected water-level scenarios, and two AHD-uncorrected scenarios for the remainder of the study's analyses and, thus, Objectives II and III.

2.6. Software and Model Environment

All inundation modelling and coastline development was created using ArcGIS Desktop 10.8.1, with the ArcCoastTools toolbox for Coastal Inundation (Enhanced Bathtub Model (eBTM)) [50]. Additionally, RC calculations and normalisations were created using QGIS 3.30 and statistics were calculated with Python 3.8.10 programming language. Water-level calculations were also calculated exclusively with Python 3.8.10 programming language.

All modelling and data collection were performed on a system Intel(R) Core(TM) i7-12700 @2.10 GHz, 12 Cores, 20 logical processors with 16 GB DDR4 RAM, and NVIDIA GeForce GTX 1660 with 6 GB of GDDR5 VRAM on Windows 10.

3. Results

During TC Debbie (2017), in the region of Mackay on the day of landfall, 28 March 2017, the Mackay Outer Harbour tide gauge recorded the highest observed water level as 3.34 m AHD-corrected, as shown in Figure 6. This study modelled scenarios with higher water levels, to simulate worst-case scenarios for the day of landfall, the month of landfall, and the landfalling TC season. As stated in Section 2.4, it is acknowledged that the analysis of the observed maximum water level would have been a valuable addition to this study; however, this will be considered in future work and serves primarily as a baseline and point of comparison in this study.

3.1. Model Comparison

All three models, the sBTM, static eBTM, and the variable eBTM were all run for Scenario 1 with a water-level height of 3.97 m AHD-corrected, 0.63 m higher than the maximum observed water level on the day of TC Debbie's landfall. This produced the results summarised in Table 2. The individual results of the sBTM and the static eBTM are also shown in Figure 7, including Figure 7c, which exclusively features the difference between the inundation extents of the two model outputs. This difference represents the entire inundation extent produced only by the sBTM, as none was produced by the static eBTM.

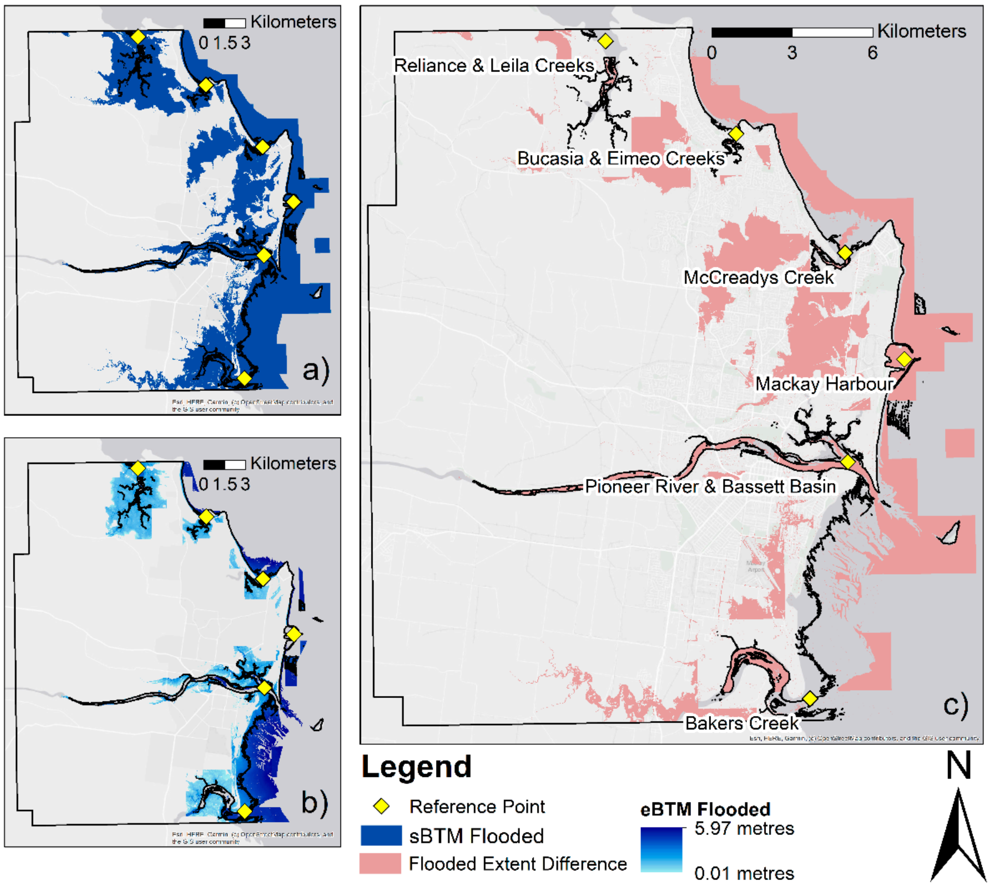

Figure 7. sBTM and static eBTM model comparison results for Scenario 1: (**a**) sBTM model output, (**b**) static eBTM model output, and (**c**) the difference in inundation extent of the sBTM and static eBTM.

Table 2. Inundation extent areas of the sBTM, static eBTM, and the variable eBTM for Scenario 1, and the percentage differences between each of the model's inundation extents.

Model	Inundation Extent Area (km^2)	% Difference to sBTM	% Difference to Static eBTM
sBTM	128.39	-	-
Static eBTM	68.67	86.98	-
Variable eBTM	68.65	87.30	0.03

As shown in Figure 7c, there was a difference in the flooded and unflooded regions of the two models, specifically 59.73 km^2, calculated by subtracting the total inundation extent of the static eBTM from the sBTM. Assuming that the static eBTM is the more "accurate" model of the two, as the static eBTM has been found to overpredict real flooding events less than sBTMs [28], the sBTM therefore overpredicted the extent of coastal inundation by 86.98%. However, as will be discussed in the discussion, there are limitations to such assumptions as the most accurate model cannot be accurately determined until there are observed inland flood extent data with which to confirm the findings; the data of which are not yet recorded in Australia. The difference in the coastal inundation extent is particularly evident when analysing the output maps further inland (Figure 7c), especially between Bucasia and Eimeo Creeks and McCreadys Creek where there is very minimal coastal inundation for the static eBTM and a lot of coastal inundation for the sBTM. This inland overprediction also appears to be consistent for the northernmost and southernmost creeks, Reliance and Leila Creeks, and Bakers Creek, respectively.

Table 2 also summarises the results of the variable eBTM for Scenario 1, where the inundation extent only differs from the results produced by the static eBTM by 0.02 km^2, a difference equivalent to 0.0055% of the total potential area that could be inundated in this study. This was calculated from a subtraction of the variable eBTM's output from the total inundation extent of the variable eBTM, as the value indicated how much the static eBTM overestimates in comparison to the variable eBTM. Therefore, if it were to be assumed that the variable eBTM was the more accurate of the two eBTMs, then the static BTM would have overpredicted the inundation extent by only 0.03%.

3.2. Variable Enhanced Bathtub Model (eBTM) Scenario Results

Figure 8 highlights one of the main outputs of this study, which shows the outputs of all three scenarios layered on each other, as shown in Figure 8a, and individually, as shown in Figure 8b–d. Figure 8a, specifically, only shows the extent of inundation for each scenario without the detail of the depth as it enhances the visible differences between the scenarios, and because the detail of the depth in each scenario is shown in Figure 8b–d. Figure 9, a close-up of Figure 8a with an adjustment of including the inundation depths, highlights an area near McCreadys Creek and on the southern bay of the Pioneer River where differences between the three models are clearer. Additionally, the edges of the inundation extent outwards of Reliance and Leila Creeks also show distinct differences at this scale.

To better highlight the differences between the scenarios, Table 3 provides a summary of the results of the scenarios run with the variable eBTM, specifically, the inputted water level, the respective surface area of the modelled inundation extent, and each Scenario's percentage difference between it and the surface areas of Scenario 1. From the results presented in this table, the results agree with the notion and expectation that as a region's water level increases, the extent of the region's coastal inundation will increase.

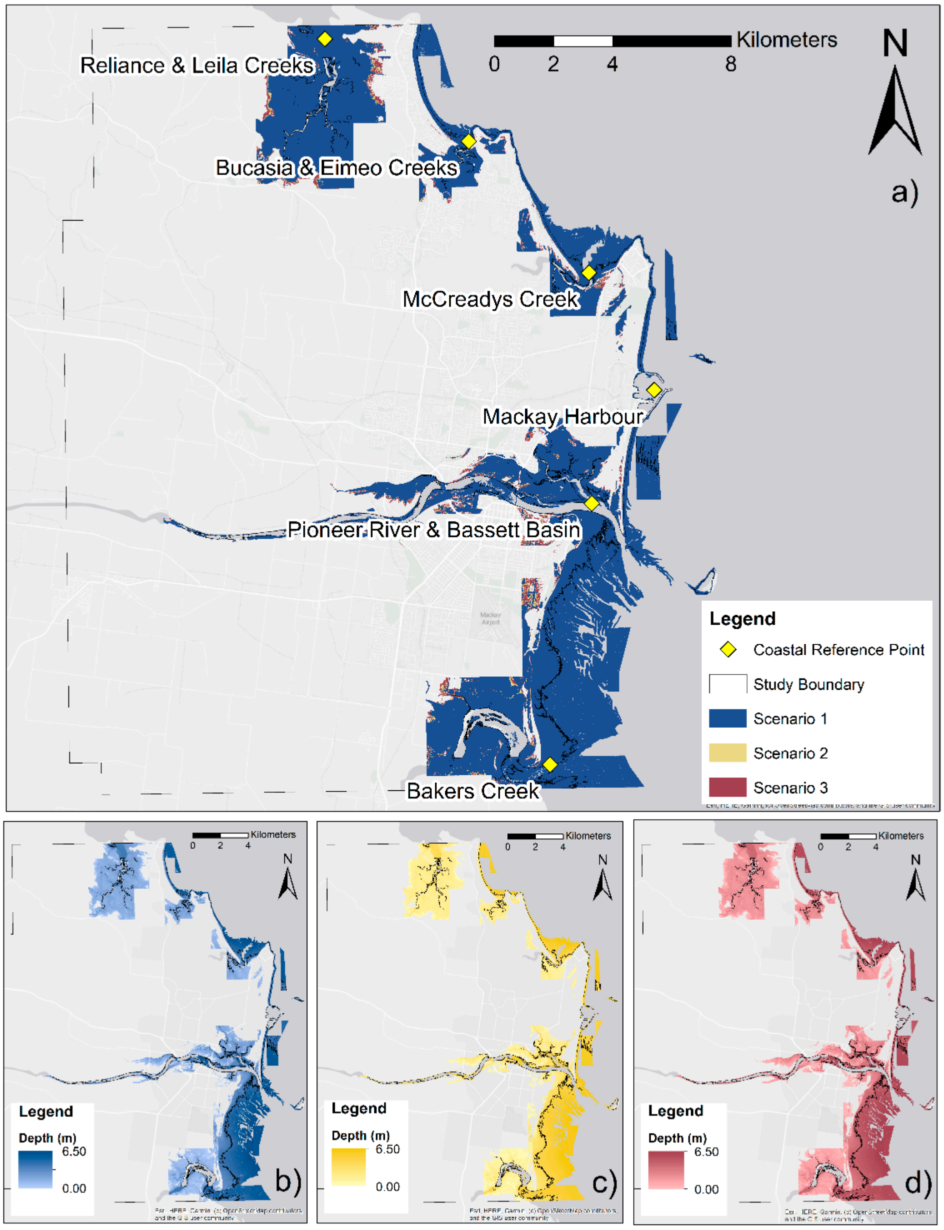

Figure 8. Map of the variable eBTMs coastal inundation prediction for (**a**) all scenarios, (**b**) Scenario 1 (3.97 m AHD), (**c**) Scenario 2 (4.10 m AHD), and (**d**) Scenario 3 (4.43 m AHD). (**b**–**d**) represent what could have been experienced if the landfalling day's maximum storm surge coincided with the maximum tide height for (**b**) the landfalling day, (**c**) the landfalling month, and (**d**) the landfalling TC season.

Table 3. A summary of the three scenarios investigated with the variable eBTM in this research study, with their AHD-corrected water-level heights, their inundation area extents, and the % difference of the inundation extent to Scenario 1.

Scenario	AHD-Corrected Water Level (m)	Inundation Extent Area (km^2)	% Difference to Scenario 1
1	3.97	68.65	-
2	4.10	69.90	1.82
3	4.43	72.53	5.65

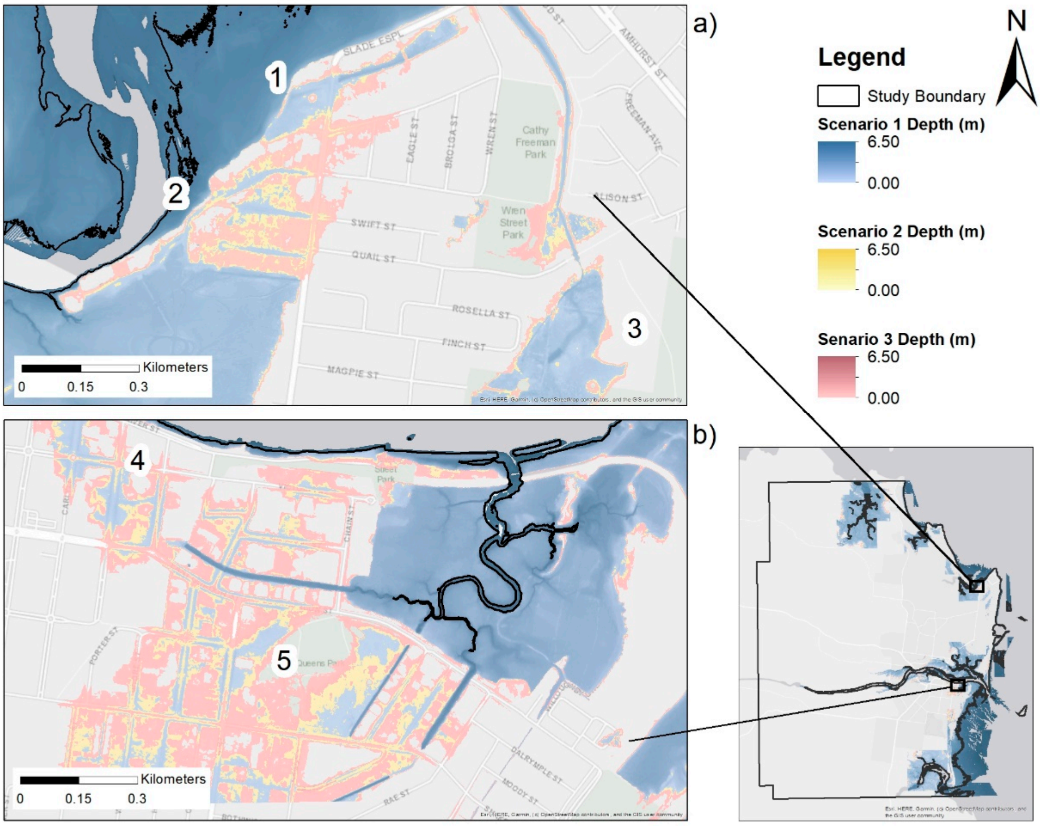

Figure 9. Map of close-ups of Figure 7, showing the stacked inundation extents of the three scenarios (top to bottom) Scenario 1, Scenario 2, and Scenario 3 (**a**) near McCreadys Creek and (**b**) on the Pioneer River.

3.3. Variable eBTM Scenario Results with Uncorrected AHD Water Levels

To consider the impact of running coastal inundation models with, and without, AHD water-level corrections, this study also ran an additional two scenarios, as summarised in Table 4. Ultimately for Scenario 1, not correcting the AHD led to an 'overestimation' of 17.90 km^2, whereas for Scenario 3, this value was 15.75 km^2. Inundation maps of these results are also shown below in Figure 10. Whilst the models showed similar regions of inundation as their AHD-corrected results, the uncorrected AHD water-level scenarios show that the depths of the floods modelled increased by nearly three metres in conjunction with flood extents expanding further inland. For example, Scenario 1's AHD-corrected inundation map shows more sparse flooding, such as along the Pioneer River, where the uncorrected AHD inundation map shows very uniform flooding on either side of the river. This trend of increasingly uniform flooding is consistent across all the flooded regions of the two scenarios.

Table 4. Differences in inundation extent areas modelled with the variable eBTM tool, where the difference represents the number of square kilometres an AHD-uncorrected water-level input would overestimate a scenario when compared to its AHD-corrected water-level input.

Scenario	AHD-Corrected Water Level (m)	AHD-Uncorrected Water Level (m)	AHD-Uncorrected Inundation Extent Area (km^2)	Inundation Extent Area Difference (km^2)	Inundation Extent Area Overestimated %
1	3.97	6.91	86.55	17.90	26.07
3	4.43	7.37	88.29	15.75	21.73

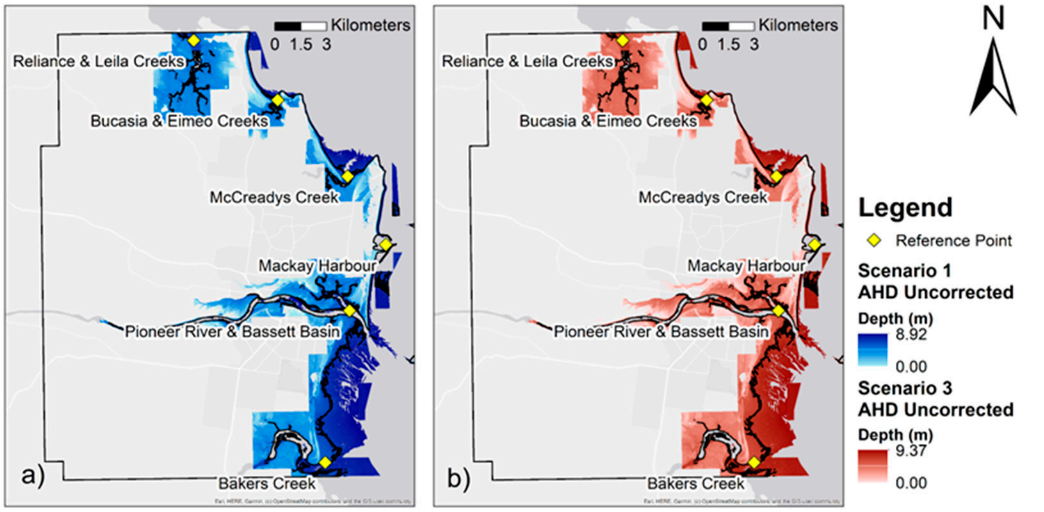

Figure 10. Maps of the uncorrected AHD water levels run with the variable eBTM for (**a**) Scenario 1 with a water level of 6.91 m and (**b**) Scenario 3 with a water level of 7.37 m.

The uncorrected AHD predicts inundation, whereas the corrected AHD does not. This is particularly evident when comparing the individual maps (Figure 8b,d and Figure 10), in areas such as behind Mackay Harbour or the region between Bucasia and Eimeo Creeks and McCready's Creek experienced flooding in the uncorrected scenarios, when they were minimally inundated in the corrected scenarios.

4. Discussion

This section will examine and analyse the predictions of inundation extents for the three worst-case scenarios for TC Debbie: What would have happened if TC Debbie's storm surge had coincided with the highest water level of the (1) day of landfall; (2) the month of landfall; or (3) the TC season, addressing Objective II. As a part of this process, Objective I was completed first, assessing the performance of the variable eBTM against the static eBTM and the sBTM. Furthermore, the implications of modelling water levels with uncorrected AHDs (Objective III), and the limitations and future directions for this work, are also discussed.

4.1. Comparing Models

This study compared the performance of the sBTM and the static eBTM to the variable eBTM, similar to a methodology used by Williams and Lück-Vogel [28]. In Williams and Lück-Vogel's [28] study in Cape Town, South Africa, they found that the sBTM consistently overestimated the inundation extent, from 12% for their least extreme scenario (1.79 m), up to 30% (2.61 m) for their most extreme scenario. For this study of the Mackay region, a comparison between the sBTM and the static eBTM resulted in the sBTM overestimating Scenario 1 (3.97 m AHD-corrected) by 86.98%, which equated to a difference of 95.73 km^2 (Table 2). These results indicate nearly three times as much overestimation between the sBTM and the static eBTM, ultimately agreeing with Williams and Lück-Vogel's [28] conclusion that the static eBTM produces a more conservative and more applicable inundation extent than the sBTM.

Mackay's higher energy coastline also complies with the sBTM's limited suitability to coastal inundation efforts, consistent with Williams and Lück-Vogel's [28] findings. Part of the differences between the two applications of the models can be explained by each study area's unique coastline and their subsequent energy levels. The uniform shape and location of Cape Town's bay indicates a low-energy environment that contrasts with the Mackay coastline, which is very inconsistent and an example of a high-energy environment, indicated by its highly variable and eroded coastline and its direct exposure to the Coral Sea [51]. In Williams and Lück-Vogel's [28] comparison of the sBTM and static eBTM, the sBTM was stated as unsuitable for modelling inundation in environments with high-energy water bodies. As the Mackay region is an even higher energy waterbody than Cape Town, the sBTM is even less. Overall, for studies modelling TC-induced inundation, one of the most extreme and high-energy causes of short-term coastal inundation, it is essential to select a model that is better suited to a high-energy environment.

This study has also observed a relationship between a study area's predicted extent of coastal inundation and the number of water body features it has; however, this is not a variable directly considered by any of the models. Because the susceptibility of water features is consistent between all three models, it means that the variable driving this relationship is shared between them all, leaving either the defined water level, or the elevation. It is unlikely that the defined water level is the direct cause for water body susceptibility to flooding, as this variable is defined by tide gauge values and is not indicative of water bodies at all. For example, a hypothetical coastline with no water body features could have the same defined water levels as this Mackay case study. Consequently, it is inferable that the elevation is the variable driving the relationship between water bodies and their susceptibility to coastal inundation. As water bodies such as creeks and rivers largely feature physical characteristics of lower elevations and smaller changes in elevation (slope) than along coastlines, such areas are thus more conducive to inland coastal inundation [46]. While this is in part due to the Mackay study region being 365 km^2, 67 times larger than the Cape Town study area of approximately 5.4 km^2, this relationship is of note as it further affirms the strong relationship between elevation and inundation extent.

The specified water levels for the applications of the models are a considerable factor that must not be ignored. For Williams and Lück-Vogel's [28] least extreme scenario, their water level was 1.79 m, and their most extreme scenario was 2.61 m. In this study on Mackay, Scenario 1 was more than twice Williams and Lück-Vogel's [28] study's least extreme scenario at 3.79 m. Though this does contribute to the differences between the two sets of comparisons, it does not negate the observed trends between characteristics of the study regions. This is attributable to Mackay's high tidal range, especially when compared to Cape Town's smaller one. The ability of the models to have relatively consistent and justifiable trends in the observations that can be drawn from their outputs highlights the flexibility of bathtub models being able to produce respectable inundation predictions regardless of the chosen study area's unique traits.

A terrain's roughness can also significantly influence the movement of water; hence, it would be reasonable to expect a significant difference in the predicted inundation extent for the static and variable eBTMs for a study area 365 km^2 in size. As the only difference between the static and variable eBTM is the RCs, discrepancies observed between the runs of the two models can reasonably be attributed to local variations in RCs. However, as shown in Table 2, the difference between the two areas is 0.02 km^2, and assuming that the variable eBTM is the "accurate" model, the static eBTM therefore overpredicted the inundation extent by only 0.03%. These differences, or their lack thereof, can be attributed to the study region's unique RCs. Though, as the RCs are calculated based on the elevation of the region, this relationship between the two eBTMs is unique to Mackay and should be noted if comparing the models in future research.

Across the three models investigated in this study, there are a couple of notable resemblances between all of their results. In Williams and Lück-Vogel's [28] work, they consistently observed that roads were conduits of water in both the sBTM and the static eBTM. In this study of Mackay, this was also observed across all three models, clearly shown in Figure 9. As roads are smooth, flat, and impermeable surfaces, they support the movement of water inland more than other surfaces such as grasslands. Whilst the model does not directly consider the real permeability of the roads featured in the study, the results do imply that roads do pose as a serious passage for water to travel along in the event of a sudden rise in sea level.

Williams and Lück-Vogel's [28] comparison of the BTMs found that the sBTM produced numerous pockets of inundation that were not hydrologically connected to the coast, whereas their application of the eBTM showed no sign of this disconnection. In this study's application of the models, it was observed in all models that there are sporadic sections of inundation with no hydrological connectivity. Locations 2 and 5 for the blue Scenario 1 model outputs of Figure 9 show some roads that the models predicted to be inundated; however, they do not appear to be hydrologically connected to any water bodies or the coastline itself. From these results, it is suggested that the eBTMs do not completely address the issue of bathtub models producing hydrologically disconnected predictions of inundation. Nonetheless, as shown in the results in Section 3.1, the eBTMs are meaningful improvements to bathtub models as they produce more conservative and applicable predictions for inundation extents.

Ultimately the variable eBTM is preferred as it provides more precise calculations of inundation extents than the static eBTM as it calculates a unique RC for every pixel in the study area, confirming the initial hypothesis that this would be the preferred model. These model comparisons inform the justification for the variable eBTM being utilised for this study's subsequent modelling of various scenarios.

4.2. Defining Water Levels

The definition of water levels is one of the main sources of novelty for this study. As established in Section 2.1, TC Debbie (2017) is known to be a "near-miss" with respect to the coastal flooding experienced by the landfall region [32], as the weather event's maximum storm surge did not coincide with high tide. Consequently, this means there is a "worst-case" scenario for TC Debbie; a scenario where the maximum storm surge does coincide with high tide. The three water-level scenarios of this study, as defined in Table 1, represent the theoretical water levels if the TC's maximum storm surge on the day of landfall had coincided with (1) the highest tide on the day of landfall, (2) the highest tide in the month of landfall, or (3) the highest tide in the TC season. To the best of our knowledge, coastal inundation scenarios have never been defined this way before, irrespective of the model applied.

In addition to the unique theoretical definition of scenarios in this study, the calculation of the water levels for the respective scenarios is also unique. Mortlock et al. [32] calculated various water-level statistics through hydrodynamic equations and utilised tide gauge and wave buoy data for the entire landfall region of TC Debbie, between Abbott Point and Hay Point. For the "maximum storm surge value", their methodology produced a maximum storm surge value of 1.12 m, whereas this study had a height of 0.99 m. The only difference in the calculation of this value was that Mortlock et al. [32] had the time frame for the maximum residual be 27–29 March 2017, whereas this study defined it as the maximum residual for the day of landfall 28 March 2017.

Additionally, for the water-level scenarios, this study determined that for Scenario 1, the maximum potential storm tide for the day of landfall was 3.97 m AHD; however, Mortlock et al. [32] calculated the maximum storm tide value to be 3.7 m. This discrepancy is the Scenario 1 value, and it added to the maximum tide on landfall day to the maximum storm surge on the day, exceeding the actual storm tide value, which is determined as the maximum of the observed data. As Mortlock et al.'s [32] study exclusively analysed the observational data, there are no comparable values for Scenarios 2 and 3.

Establishing the water levels through an analysis of the TC season's tide gauge data and utilising it to define unique water levels for three scenarios is another source of novelty in this study. For coastal inundation modelling, especially in the context of its applications to inform decision makers, hydrodynamic models are the most highly regarded [52–54]. One of the core inputs of these models is the tide gauge data, as they partially account for the observable hydrodynamics of waves and general water levels. As a result, a GIS-based bathtub model for coastal inundation that considers observations from tide gauge data, like this study, contributes to the reputability of bathtub models.

4.3. Impacts of "Worst-Case Scenarios" for Tropical Cyclone Debbie

The model output for Scenario 1 shows a prediction of the potential inundation expected if TC Debbie's maximum storm surge had coincided with its highest tide on the day of landfall (Figure 8b). Although this water-level value is theoretical, it does represent the worst-case scenario for TC Debbie on its day of landfall. In Mortlock et al.'s study [32], they concluded that if the TC had made landfall only two hours earlier, the overall storm tide would have been higher, and it would have caused widespread flooding; Scenario 1 models the resulting inundation of a water level very similar to Mortlock et al.'s [32] hypothetical water level. Further extending this theoretical idea, we reach Scenarios 2 and 3 where we explored what would have occurred if this storm surge had coincided with the highest tide of the month of landfall and the TC season.

The model showed that for the entire study area, 68.65 km^2 was inundated, with flood depths reaching 5.97 m for Scenario 1, which has an inundation water level of 3.97 m AHD-corrected (Figure 8b). From visual inspection of the main figure, the flooded regions for this scenario sparsely show the inundation of residential property. The few instances of inundated properties are shown in Locations 1–2 and 4–5 in Figure 9, and through utilising the identifying feature of ArcGIS Desktop 10.8.1, the inundation depths of these properties reached a maximum of ~0.25 m AHD. These observations imply that for Scenario 1, the model determines that there was likely minimal damage as a result of inundation, for the region of Mackay.

The Scenario 1 results also agree with another observation found for most bathtub models; the closer a location is to a water body such as a creek or river, the more likely it is to be inundated. This is largely attributable to the principle of hydrological connectivity, which implies that a location can only be flooded if it is hydrologically connected to a water source, such as the coast or a river. Therefore, the output of Scenario 1 also mostly behaves appropriately with respect to hydrological connectivity. Whilst there are some instances of hydrological discontinuity such as the blue Scenario 1 outputs of Figure 9 at Location 3 and 5 in Figure 9, this may be a limitation of the variable eBTM's definition of hydrological connectivity for a region as hydrologically complex as Mackay.

Scenario 2 models the potential coastal inundation event if TC Debbie made landfall at the same time as the highest tide of the month. The output of Scenario 2, which had an AHD-corrected water level of 4.10 m, produced an inundation extent of 69.90 km^2, reaching flood depths up to 6.10 m (Figure 8c). In comparison to the results and observations for Scenario 1, this model experienced 1.25 km^2 more inundation, for an increased water level of 0.13 m. The increased inundation extent is shown in Figure 9, where flood extents of Scenario 2 (yellow) did not extend much further than that of Scenario 1 (blue).

Following consideration of Scenario 2, which was a hypothetical scenario analysing TC Debbie's highest possible water level for the month of landfall, the inundation extent could have been even more severe. TCs typically occur during the TC season, which in the Southern Hemisphere is usually from November to April. Thus, it is reasonable to hypothesise that TC Debbie could have taken place at any point between November 2016 and April 2017. Determining a feasible, absolute worst-case scenario for TC Debbie's coastal inundation would therefore be achieved by answering the question of what if the highest tide of the TC season had coincided with the maximum storm surge of TC Debbie.

Scenario 3's results, presented in Figure 8d, show 72.23 km^2 of flooded coast, for a water level of 4.43 m. Reaching up to 6.43 m in depth, this scenario represents TC Debbie's worst-case scenario. Compared with Scenarios 1 and 2's inundation extents, Scenario 3's results imply that it respectively caused 2.63 km^2 and 3.88 km^2 more inundation. Similar to the observations made in Section 4.2 for Scenario 2, visual inspections of Figure 8a, which show the results of all the inundation scenarios, revealed that the general locations of inundation remained quite consistent. However, the same two regions shown in Figure 9 continued to experience some of the most drastic changes to their inundation extent.

In terms of inundation depths, Figure 8b primarily shows where flooding is scarce and nearly exclusive to the roads, which act as water conduits, where few properties are partially inundated for Scenario 1. Figure 8c shows the same region for Scenario 2 where general locations of flooding have not changed drastically; however, the inundation is much more uniform and with more properties experiencing inundation, reaching depths up to ~0.50 m. Across the inundation outputs for the two scenarios, this trend of increasingly uniform and deeper flooding is observed, with the region in Figure 8c,d showing the most severe change between models. The main differences between Scenarios 1 and 2 indicate that despite an increase of only 0.13 m at the coastline water level, and an inundation extent increase of 1.82%, there was a notable increase in the proportion of properties and roads inundated.

For Scenario 3, the modelled flooding extent is even more uniform than that presented for Scenario 2. Even though the location of flooding stayed quite consistent and only expanded slightly, even more properties are modelled to be completely inundated. In Scenarios 1 and 2, there were still large pockets in these locations that were completely free of inundation; however, for Scenario 3, there are very few of these unflooded pockets; those remaining are also quite small. Consequently, many properties have been inundated in this scenario, reaching depths of up to ~1.00 m. Ultimately, the observations found comparing Scenarios 1 and 2 are also applicable in comparisons of them with Scenario 3; the rise in water level leads to a considerable increase in the proportion of properties inundated.

The results of this study primarily predict that for the worst-case scenario of TC Debbie, 72.53 km^2 of coastal inundation would be experienced by the Mackay region. This was represented by Scenario 3, where the defined water level of 4.43 m AHD-corrected was 1.09 m higher than the highest observed water level in the event itself. The area difference between this worst-case scenario, and the least severe worst-case scenario of Scenario 1 (3.97 m AHD) is 3.88 km^2, indicating that Scenario 3 showed 5.65% more inundation than Scenario 3. This is particularly interesting as Scenario 3 was only 0.33 m higher than Scenario 2, which showed only 1.92% more inundation than Scenario 1 (1.25 km^2). These results suggest that as the scenarios become more extreme, such as for Scenario 3, more coastal inundation is predicted for a similar change in water level. Yet, as the study only has these three sets of values, there are thus insufficient data to investigate this potential relationship further. Additionally, this may also be caused by the unique topography of Mackay, rather than be driven by the defined water levels. Ultimately, it means that the additional inundation expected for a 0.33 m water-level rise (between Scenarios 2 and 3) cannot directly be inferred from the inundation predicted from a previous rise of 0.13 m (between Scenarios 1 and 2).

Through the use of the variable eBTM, the results also support the notion that variables such as the topography, roughness, and slope of terrains serve as reliable indicators of the predicted inundation. Whilst the sBTM produced results for inundation, its only inputs are the water level investigated and the elevation of the study area. As there is minimal information considered, this is the likely cause for the unreliability of the sBTMs, as shown in the significant difference between the results produced by them and the eBTMs (Table 2). Given there is a more reliable inundation extent produced from the eBTMs, in this study, and from Williams and Lück-Vogel's [28], suggests that the beach slope, terrain roughness, and/or the hydrological connectivity all either individually or collectively play a significant role in the behaviour of coastal flooding.

Throughout this study, a number of its findings in Section 4.1 support those established in the original study [28]. Firstly, the proximity of a location to the coastline is not trivially indicative of the inundation it could experience. Though there are regions of the study with inundation uniform with the coastline, such as along Mackay Harbour (see Figure 8), this is not the case for most of the study region. From visual inspection of the maps, it is apparent that a location's proximity to a large water body is much more indicative of whether it will be flooded or not, as was discussed in Section 4.2. Furthermore, both studies observed that roads act as conduits of water, as was discussed in Section 4.1, which discussed the results of comparing the sBTM, static eBTM, and variable eBTM.

These findings, observations and their implications emphasise the need for location-specific coastal inundation. The results support that terrain-specific features such as the proximity to water bodies or the elevation of a terrain are significant influencers of inundation extent. As a result, it also means that the inundation results of this study are inapplicable to other studies as they are unique to the Mackay region. However, the findings of this study and those like it are invaluable for assessing potential exposure to storm surge hazards. Such results can be utilised by decision makers in developing the appropriate mitigation strategies and perhaps even policies.

4.4. Impacts of Uncorrected AHD Water Levels

Unfortunately, there are still some instances where the AHD corrections are not specified, such as with Burston, Symonds, and Tomlinson's [55] study; doing so leaves readers to assume whether AHD corrections were performed or not. Hence, the explicit consideration of AHD in a study allows for consistent and transparent comparison and repeatability of studies, as this study was able to do with Mortlock et al.'s [32] study, for the definition of water levels. It also ensures that the water levels and other data, such as the elevation data, have been matched up appropriately. If this is not carefully considered it can lead to dramatic over or underestimations of the inundation extent.

In this study, the differences between modelling the coastal inundation of the Mackay region with uncorrected and corrected water levels were investigated, and these results are presented in Section 3.3. These results show that the uncorrected AHD water levels would lead to overestimations of 26.07% (17.90 km^2) for Scenario 1 and 21.73% (15.75 km^2) for Scenario 3. These results are all consistent with the original study's observation that higher water-level scenarios show dramatic increases in inundation [28]. This therefore agrees with the hypothesis that the lack of including AHD corrections can lead to notable differences in predictions. Ensuring more explicit specifications of AHD corrections in the methodologies of future research also supports the long-term homogenisation and comparison of TC and storm-tide-related work and records.

The inclusion of the AHD in the calculation of water levels is generally found in academic work, for example, Granger and Smith's [56] inundation modelling, as well as Haigh et al.'s [34] work on hydrodynamic hazard assessments of TC-induced storm surges. However, as discussed earlier for works such as Burston, Symonds, and Tomlinson's [55] study, there have been studies where this was never directly addressed. For a study area such as Mackay, where this correction is equivalent to 2.94 m, this difference is noteworthy, though it is unique to this location and such a large correction is uncommon. In a study by Hague et al. [57], the development of thresholds for non-TC-induced coastal inundation for Australia's northern coastline was analysed. Whilst AHD corrections were not explicitly considered in their work, it acknowledged the importance of considering common datums such as the AHD as valuable extensions to coastal inundation work.

4.5. Limitations

One of the limitations of this study is the lack of observed TC-induced coastal inundation data. It is standard for climate-related models to be validated against past observations similar to the event being modelled. In the case of TC-induced coastal inundation, observed data appropriate for the validation of such models would be any measurements of the depth of inland water, during a TC event. Williams and Lück-Vogel [28] explored non-TC storm-induced storm surges, where the static eBTM results were compared to three flood line markers. Thus, in their study, Williams and Lück-Vogel [28] confirmed that for that application's circumstances, the static eBTM indicated reliable results. Some observations of non-TC-related coastal inundation have been recorded, as used in the study by Hague et al. [57]; however, the data were limited and not relevant for this study and were therefore inappropriate as a method for validating this study's model. Not only does the lack of validation data prevent establishment of the reliability of the model, but it also hinders future development of models as it is usually through this validation process that a developer can identify sources of errors to address.

In addition to the lack of observed coastal inundation data, the study is also limited by Mackay's singular tide gauge. Haigh et al. [34] found that Australia's tide gauge records inadequately describe regional climatology. Hence, this study's assessment of coastal inundation utilising only the data obtained from the Mackay tide gauge is increasingly limited further away from the tide gauge. The main concern with this approach is that it assumes the entire coastline of this study has a uniform water level. Due to the complexity of the Australian coastline, this is improbable, especially considering that Mackay itself has very unique and highly variable tidal characteristics. Regardless of the models to which they apply, it is agreed in any efforts regarding coastal flooding that more detailed sea-level data are necessary to support future work. Furthermore, despite it not being a direct limitation for the Mackay case study, the variable eBTM's inability to specify more than one water level for the whole coastline means that even if a region has more than one gauge, it is not possible to directly incorporate the extra information from the additional gauges. This study's methodology would require modification if a study area featured more than one tide gauge. Developing the model to allow for multiple points of the coastline to have a unique water level is thus an improvement to the model that can be justified without validation data.

Beyond data availability and the inability to consider more than one water level on a coastline, the model is also limited by its disregard for more dynamic processes such as wave runup and wind push [28]. This is because the inclusion of such processes requires the expertise and computational power of work performed with hydrodynamic models, due to their complexity. Despite this study primarily considering the impact of storm surges through calculating storm tides, it has been analysed that for TC Debbie, they were attributable to 84% of total water levels, whereas other coastal features were only linked to 16% of the total [32]. As a result, this model does consider the most important process of storm surges despite not considering all processes that occur in a TC.

5. Conclusions

Through the implementation of the variable eBTM, this study investigated three worst-case scenarios for potential inundation in the Mackay region caused by storm surges generated by TC Debbie (2017). It was found that between the least and most severe scenarios for TC Debbie's hypothetical impact, with the input water-level difference for the model along the coastline being 0.43 m, the observed inundation depth of the analysed populated region increased from 0.25 m to 1 m. These two scenarios also indicated that this change in the water level led to an additional 3.88 km^2 (5.65%) of inundation past the coastlines, compared to the least severe 'worst-case' scenario.

In the analysis of the impact of modelling with uncorrected AHD water levels, this study confirms that the explicit inclusion of AHD corrections is imperative. This is especially the case for regions such as Mackay where this correction is a difference of 2.94 m and, ultimately, resulted in predicted inundation extents overestimating by 17.90 km^2 (26.07%).

This study also determined that of the three models, the sBTM, the static eBTM, and the variable eBTM, the variable eBTM is the optimal model. Regarding the static and variable eBTMs, it was found that for the Mackay region, the two models only differed by 0.02 km^2 (0.0055%). However, as the only difference between the models was the definition of RCs, and that the majority of the study area has an RC value of 0.01, this difference is unique to the Mackay region and may be further investigated in study areas with different terrains.

Additionally, this study found that locations close in proximity to water bodies, such as creeks or rivers, were much more susceptible to coastal inundation than areas less so. Furthermore, roads in all scenarios and models were clearly presented as conduits of water, implying that such structures support the inland movement of ocean water due to their smoothness and low permeability.

Ultimately, further application and development of the variable eBTM is supported by the findings of this study. In particular, the use of such models, which are accessible yet informative, is a viable tool for providing preliminary coastal inundation hazard assessments, to better inform decision makers and communities of the potential impacts of TC-induced storm surges.

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Appendix A

All tide gauge data were obtained through this link: https://www.msq.qld.gov.au/Tides/Open-data accessed on 28 April 2023. Below is a table showing all of the direct links to the tide gauge data utilised in this study.

Years	Category	Link to Description	Link to Source
2011–2016	Historical/Observed	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-archived-interval-recordings/resource/f4bc0ac0-00b7-4d9d-9c87-2f9a234d262a?inner_span=True (accessed on 28 April 2023)	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-archived-interval-recordings/resource/e972f6ba-d377-4864-ba18-c222ea855824?inner_span=True (accessed on 28 April 2023)
2017	Historical/Observed	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-archived-interval-recordings/resource/f4bc0ac0-00b7-4d9d-9c87-2f9a234d262a?inner_span=True (accessed on 28 April 2023)	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-archived-interval-recordings/resource/5870ef81-c050-4dcb-99fb-c650e0a4841e (accessed on 28 April 2023)
2011–2016	Tide/Predicted	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-predicted-interval-data/resource/517c2c0b-1f00-47e8-b766-6fc54b2ade0d (accessed on 28 April 2023)	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-predicted-interval-data/resource/dd4150e9-2df7-4779-bc2a-163e916f3ae8?inner_span=True (accessed on 28 April 2023)
2017	Tide/Predicted	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-predicted-interval-data/resource/517c2c0b-1f00-47e8-b766-6fc54b2ade0d (accessed on 28 April 2023)	https://www.data.qld.gov.au/dataset/mackay-tide-gauge-predicted-interval-data/resource/592abc0e-a5f2-4547-9121-7a04d87b7851 (accessed on 28 April 2023)

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