

Article

Assessment of Coastal Compound Flooding in Tropical Catchment: Saltwater Creek Catchment in Australia

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Abstract

Compound flooding in coastal tropical cities is becoming increasingly prominent, driven by extreme rainfall events and sea level rise, under a changing climate. Quantifying the impact of these events is limited due to a lack of long-term data and funding and the need for advanced computational tools. To address this issue, this study employed a coupled one-dimensional (1D) and two-dimensional (2D) hydrodynamic model for the Saltwater Creek catchment in tropical north Queensland, Australia. In total, eight scenarios with compounding effects were assessed: four under the current climate (CC) and four under representative concentration pathway (RCP) 8.5. Under CC, the compound flooding event inundated almost 3% to 18% of the area conditions. This condition is further exacerbated under the RCP 8.5 climate change scenario, expanding the area flooded by 2% to 7% by 2090. The site experiences inundation up to 4.6 m at low-lying locations and extreme velocities up to 4 m/s at the upstream catchment with high flooding risk. The results suggest that this catchment requires an integrated approach to flood mitigation to meet the challenges posed by climate change, but careful consideration is required in interpreting the results. The results can be further improved by adopting higher-resolution and longer datasets for modelling, as well as considering land use change under the climate change scenarios.

Keywords: compound flooding; hydrodynamic model; tropical climate; coastal inundation; climate change



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1. Introduction

Flooding is a serious and universal hazard, resulting in economic, social, and environmental damage [1–3]. It is a rapidly growing threat to most coastal regions due to alterations in rainfall intensity, sea level rise (SLR), and the intensification of cyclones driven by climate change [4]. Tropical coastal cities located in low-lying areas are highly vulnerable to flooding [5]. Approximately 62% of the global low-lying area, with an elevation of less than two meters above sea level, is in tropical regions. Urbanisation in these low-lying plains has exposed the population and development activities to an increased risk

of flooding [6,7]. The interaction between natural processes and anthropogenic activities has increasingly transformed coastal flooding into complex compound events [7,8].

Compound events are combinations or successive occurrences of two or more flood drivers leading to substantial exacerbation of flood extent, depth, and duration, thereby resulting in more severe damage to life and property [8,9]. Previous studies in tropical regions have primarily concentrated on evaluating individual flood drivers, such as pluvial flooding due to extreme rainfall and river flooding [10]. Although these studies provide valuable insights, their emphasis on individual factors for evaluating flooding behaviour offers an inadequate understanding and visualisation of the compound flooding problem, particularly in tropical coastal cities. Relying solely on these outcomes results in insufficient preparedness and potential failure of flood mitigation measures, exposing communities to a greater risk of flood impacts [3].

Recently, the risk from compound events has become prominent in tropical cities [7,11–13]. Projected climate change outcomes indicate that compound flooding will likely become the new normal in the future [4]. However, evaluations of this complex phenomenon are limited due to the need for tools with high computational power at a reasonable cost, acceptable processing times, and comprehensive data to provide an in-depth understanding of the phenomenon [14–18]. The availability of such resources, primarily in extra-tropical locations, has provided opportunities to model these complex phenomena [19–21]. Nevertheless, in tropical catchments, relatively few studies have tried to understand the interactions between extreme precipitation-caused pluvial, river, and coastal flooding [10,22]. Many tropical areas encounter challenges in conducting such studies due to a lack of high-resolution digital elevation models, flood records, and research resources.

Compound modelling can be performed by connecting numerical models by linking techniques, loose coupling, tight coupling, and full coupling [20]. Here, linking techniques use the transfer of results from one model to another, loose-coupling approaches couple models that run separately but interact with each other, and the tight-coupling method combines independent models into a single modelling platform. Full-coupling approaches solve each process, such as rainfall runoff and storm surge, simultaneously with a single platform. The availability of such tools lately has increased activity in the modelling of such events globally. On the other hand, there are several approaches presenting flooding results, including flood recurrence intervals, inundation depth, flood hazard maps, and flood hazard index [23–25].

Particularly in wet tropical catchments, a quantitative assessment of compound flooding is critical for urban planning, the development of flood mitigation measures, and disaster preparedness [26]. Few studies have discussed these phenomena, mostly in tropical climates, although the occurrence and impact of such events are severe in these catchments [27]. However, our current understanding of flooding is based on an analysis of individual flood phenomena, which is not enough to guide future adaptation, as it does not effectively characterise the potential future impact of compound flooding. Alternatively, assessing the combined effect of numerous significant factors presents a complex problem that consistently results in high uncertainty and errors. A comprehensive understanding of such events can inform future flood mitigation technologies and decrease flood risk in the context of climate change scenarios [11,21]. The outcomes of such studies should be indicators of a range of possibilities, rather than being regarded as conclusive. Nonetheless, these study outcomes are essential for ensuring that adaptation planning is informed by information and is realistic.

Therefore, this study has adopted a scenario-based approach of modelling using a coupled hydrodynamic model to examine the impact of compound flooding in a wet tropical catchment. This study aims to address the following questions regarding current

and future climate change: (i) How does compound flooding propagate in a wet tropical catchment? (ii) How does climate change impact this compound flooding?

2. Materials and Methods

2.1. Study Area

Saltwater Creek is a short, moderately steep, mixed urban–forest catchment with a total area of 16 km² in the far northern tropical coastal city of Cairns, Queensland, Australia. This study considers 9.09 km² (57%) of the total catchment area as the study site. This fraction of the total catchment area selected for the study site was determined based on the water level measured at the drainage outlet (Figure 1). The catchment length (from west to east) is ~6 km, and its elevation ranges from −0.11 m to 354 m above Australian Height Datum (AHD; average sea level). The steep headwaters make the catchment highly responsive to rainfall events.

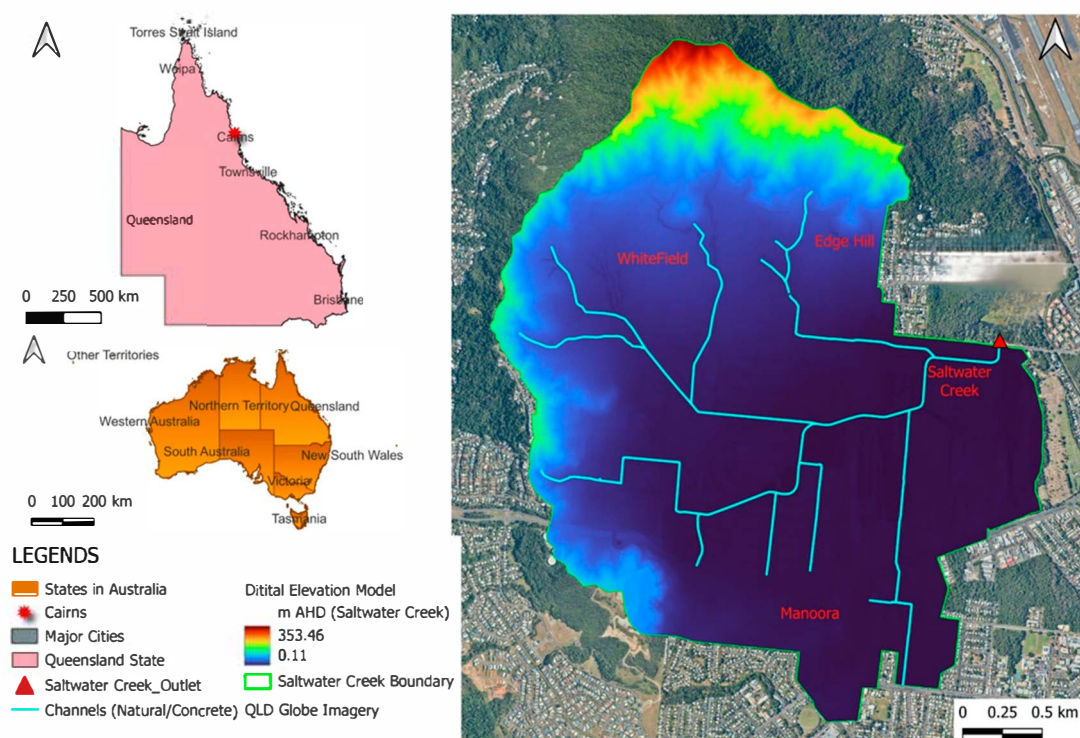


Figure 1. Saltwater Creek catchment (study site) in Cairns City, Queensland, Australia, including the drainage network and digital elevation model, with key features shown.

Saltwater Creek is a complex catchment featuring numerous interconnected natural and artificial drainage networks, as shown in Figure 1. This catchment encompasses a diverse range of land uses and land covers, including residential buildings, roads, business areas, public buildings (such as schools), a botanical garden, open parks, a wetland, lagoons, and a tropical rainforest located at the upstream end of the catchment. In addition, this catchment demonstrates multiple interactions between several water bodies, adding further complexities to understanding flood hazards. The runoff discharged from urban areas is intercepted by grey measures, such as those on roads and roofs. It is redirected to the nearest natural stream and the artificial drainage network connected to Saltwater Creek, ultimately discharging into the ocean. Due to its low-lying topography, it is vulnerable to the impacts of tidal inundation and sea level rise due to climate change. These interactions have led to past instances of pluvial, fluvial, and coastal flooding. Compound flooding is expected to continue and intensify, driven by climate change. Consequently, Saltwater

Creek serves as an ideal study site for understanding the dynamics of compound flooding in tropical catchments.

The Australian Bureau of Meteorology (BOM) classifies Cairns as part of the wet tropical climatic zone. This city experiences an annual average rainfall (1942–2024) that ranges between 1997 mm and 3148 mm. The maximum monthly precipitation during the wet season, from December to April, can reach 1417 mm, while the rest of the year remains predominantly dry, from July to November. Cairns experiences temperatures ranging from a mean maximum of 29.4 °C to a mean minimum of 21.0 °C; however, the maximum temperature can rise to 42.6 °C during hot, humid summer days.

2.2. Datasets

2.2.1. Digital Elevation Model (DEM)

A high-resolution 0.5×0.5 m digital elevation model (DEM) was generated from 2021 Light Detection and Ranging (LiDAR) data obtained from the Cairns Regional Council (CRC). The DEM defines the catchment topography, as demonstrated in Figure 1, and has been utilised in this study for catchment delineation and underpinning hydrological and hydraulic modelling.

2.2.2. Rainfall

The climate record from the Cairns Aero Station (31011), located at a latitude of -16.87° N and a longitude of 145.75° E, spanning the period from 1943 to 2024, was analysed [28]. The rainfall, water level, and tidal level data were collected using different instruments, maintained by the CRC and the Queensland government [29]. The features such as rain gauges, tidal stations, and sensor location at the outlet of Saltwater Creek are highlighted in Figure 2.

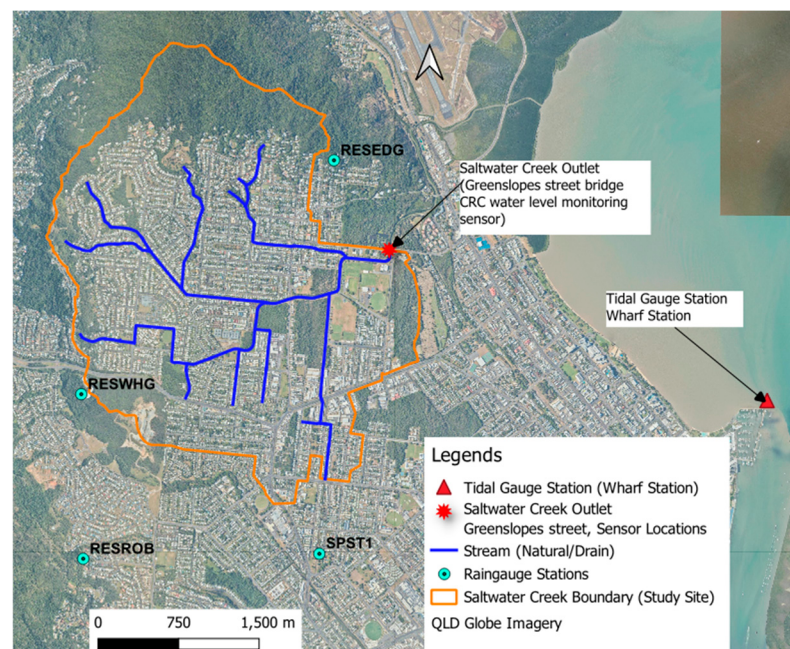


Figure 2. Rain gauge, tidal gauge station, pressure transducer at the outlet, and drainage network within the Saltwater Creek study site.

The rainfall data were supplied as cumulative totals at five-minute intervals over a day, with the accumulation resetting to zero at the end of every day. The IDW method was adopted to spatially distribute rainfall using interpolation from the sub-catchment centroid to the whole catchment [30], as shown in Figure 3.

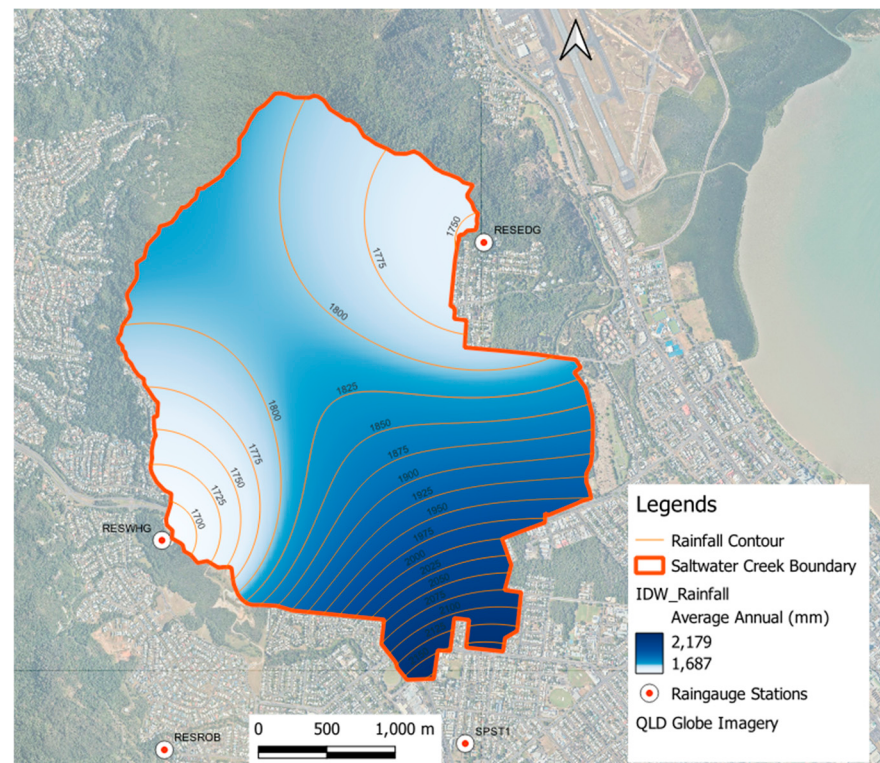


Figure 3. Inverse distance weighting (IDW) interpolation of average annual precipitation estimation of Saltwater Creek catchment for the period of 2019 to 2024.

2.2.3. Water Level

A pressure transducer was installed to collect water level every 5 min from 2019 to 2024 by CRC [31]. Water level data for model calibration and validation were collected by CRC at the catchment outlet. A hydrograph of water level and rainfall data was prepared to check the consistency of the data as presented in Figure 4.

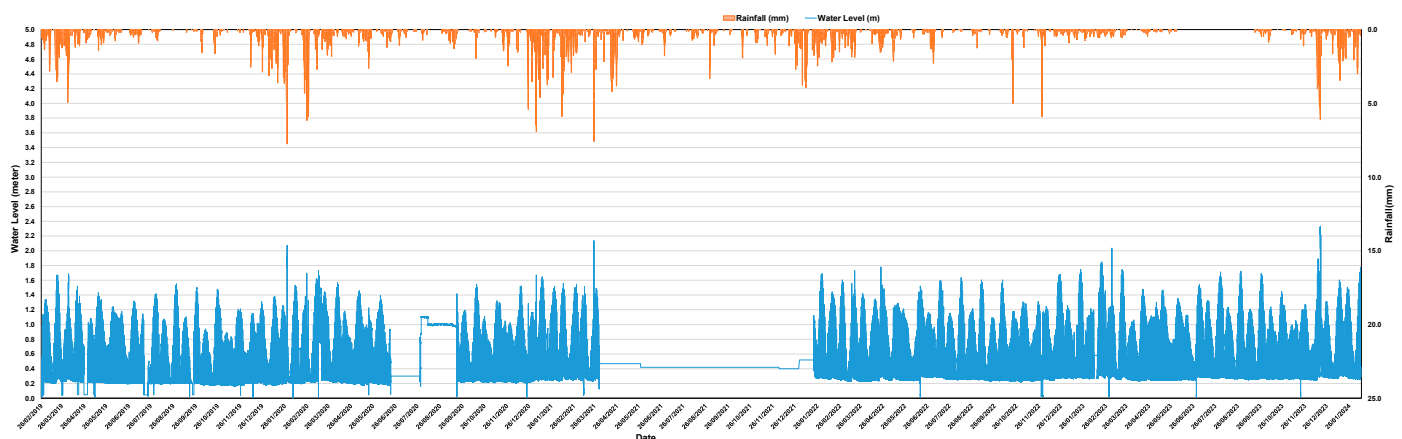


Figure 4. Water level time series measured by a pressure transducer sensor at the Greenslopes Street Bridge site, Saltwater Creek catchment outlet.

Flow velocity measurements were conducted at the Greenslopes Street sensor location to develop the rating curve for model calibration and validation. A portable current meter was employed, with water level measurements made using a levelling staff [32]. The water level recorded during the velocity measurement was later cross-checked against the sensor water level data for validation. The tidal and non-tidal flow velocity components were separated by comparing the flow velocity with the water level and rainfall data. The tidally

influenced data points were excluded from the analysis, and only rainfall-driven flow was utilised to develop the rating curve. The discharge calculated from this data was further used to develop the rating curve (Figure 5), which was later employed for model calibration and validation.

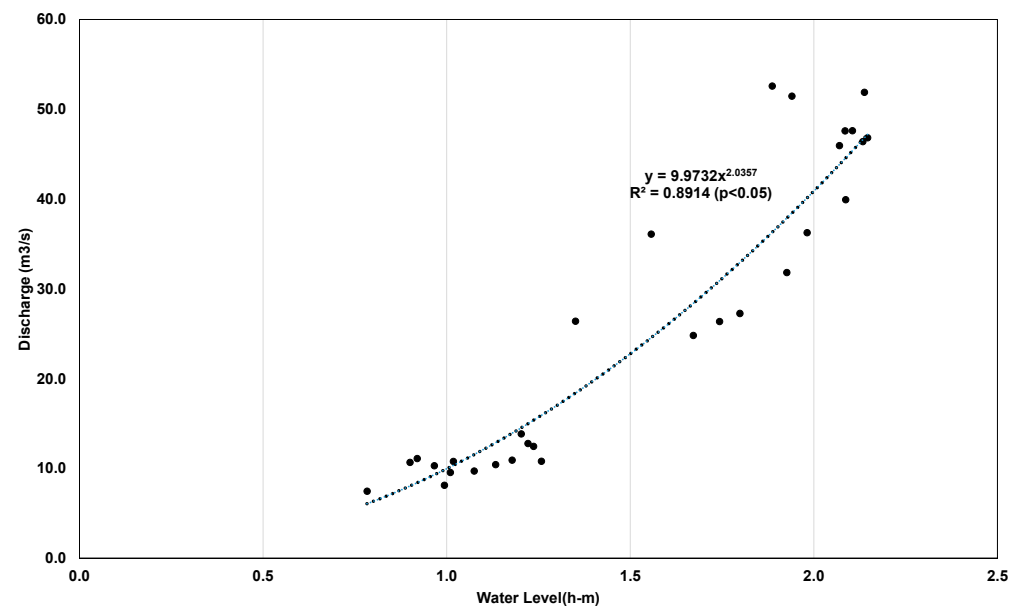


Figure 5. Rating curve for Saltwater Creek at Greenslopes Street Bridge Outlet for rainfall runoff flow only.

2.2.4. Tidal Datasets

Storm tide data is another critical data required for understanding flood hazards in this catchment. Every 10 min, tidal level data were obtained from the Cairns Storm Surge No. 7 Wharf tide gauge (Figure 2) via the Queensland Government's open data portal [29]. The lag time between the tidal cycle and its impact at the Greenslopes Street outflow was calculated, revealing a maximum lag time of 10 to 20 min, which was deemed insignificant. However, tidal data were used for modelling, adjusted for this lag time. This short lag may be attributed to the equidistant location of both sensors (approximately 4.5 km) from the tidal divergence points inside Saltwater Creek to the Wharf Station, where the tidal measurements are taken.

2.2.5. Hydrological Data

The areal temporal patterns (ATPs), areal reduction factors (ARFs), and losses were downloaded from the ARR Data Hub website for the study site. Here, ATP refers to a data type that illustrates how rainfall data varies over time within the catchment; this is essential for providing a realistic simulation of storm behaviour [33]. ARFs adjust the point rainfall data to reflect average rainfall over a large catchment. Intensity–frequency–duration (IFD) data were downloaded from the BOM website, which lists frequent and infrequent events extending from 1% Annual Exceedance Probability (AEP) corresponding to a 100-year return period to 63.2% AEP (1.58 years) with durations ranging from 1 min to 168 h, as shown in Figure 6. The IFD data provides information on estimated extreme rainfall intensities over different durations and return periods.

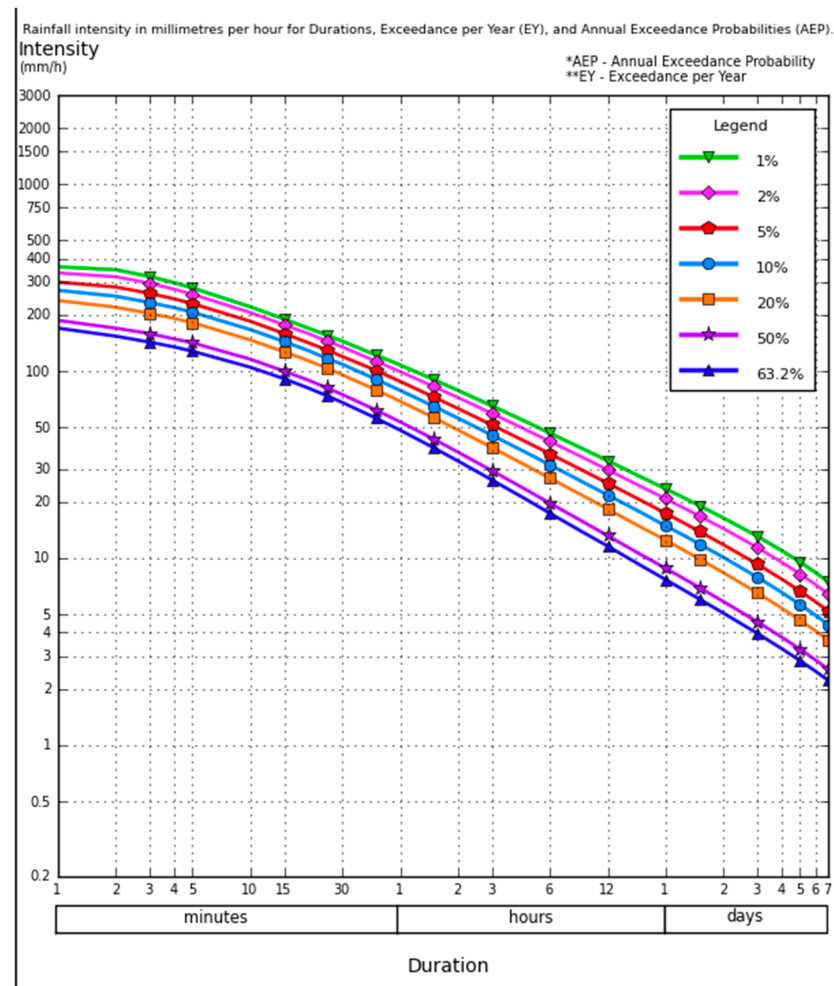


Figure 6. IFD design rainfall intensity (mm/h) for Saltwater Creek catchment.

2.2.6. Land Use/Land Cover

Land use and land cover data were obtained from the Cairns Council. The classification for land use areas encompasses rooftops, roads, driveways, forests, open spaces, swimming pools, wetlands, and creeks, as illustrated in Figure 7. The precision of these datasets was further validated through desk verification, consultations with the relevant authorities, field inspections, on-ground measurements, and utilisation of Queensland Globe [34].

An urban catchment can be generally divided into impervious areas with direct connection to drainage (DCIA), impervious surfaces without direct connection (ICIA), and pervious or semi-pervious surfaces [35]. DCIA is the division of total impervious area (TIA) that is hydraulically linked to the drainage system, serving as a reliable catchment boundary for determining actual urban runoff [36]. In addition, ICIA is a division of TIA that does not have a direct runoff contribution to the drainage network. Quantifying these values is critical to improving rainfall runoff modelling, with the catchment comprising 47% DCIA, 27% ICIA, and 27% pervious surfaces.

The maximum area is occupied by forest, followed by green space. Pools and wetlands cover the least area. The impervious area, composed of buildings, roads, pavements, and pools, accounts for almost 47% of this catchment.

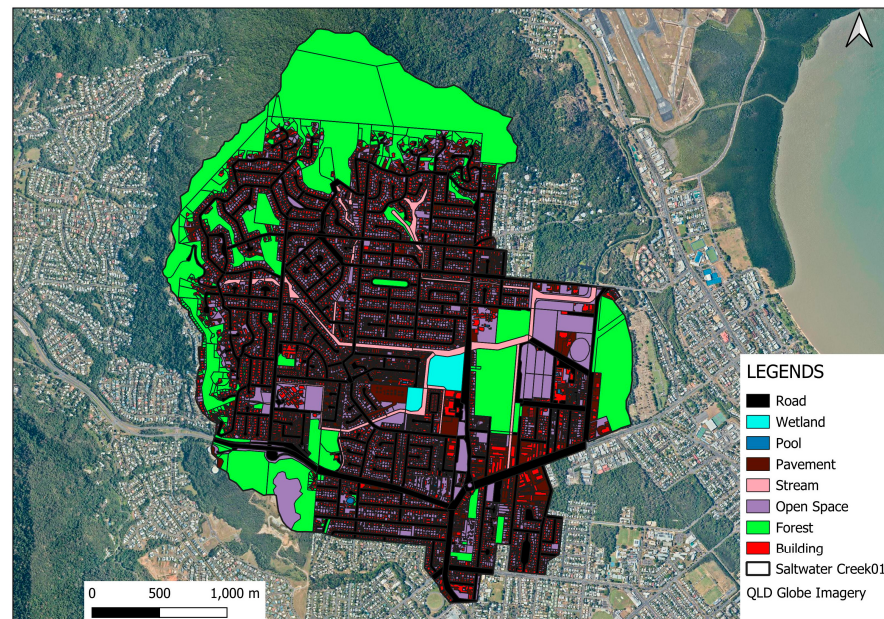


Figure 7. Land use/land cover map of the Saltwater Creek catchment.

2.2.7. Drainage Data

Currently, the council manages stormwater runoff using grey infrastructure technologies such as pipe networks, manholes, inlets, and discharges into the nearest natural or partially paved open concrete channels, as shown in Figure 8. Manholes and inlets collect the runoff from the road and open spaces during the rainfall runoff process. In addition, pipe networks and channels are functional for the temporary storage and transportation of runoff intercepted by the inlets and manholes. Furthermore, the outlets discharge the runoff to water bodies, while culverts help to transport runoff across the road. The inclusion of such data during flooding modelling affects the predictions of flood locations and extents, which allows a better depiction of the flow dynamics linking overland and pipe system flows [37]. This data was gathered from the council team, followed by a desk study, consultations, and field measurements to further validate the data.

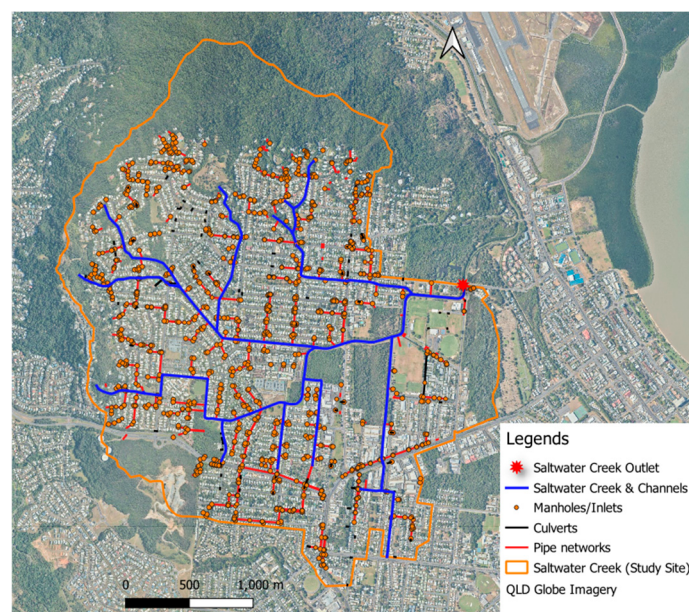


Figure 8. Natural and existing artificial channels and existing pipe network, inlets, manholes, culverts, and grey measures in the Saltwater Creek catchment.

2.2.8. Geology and Soil Type

The geological and soil types in the Saltwater Creek catchment are underlain by the highly deformed meta-sedimentary Hodgkinson Formation [38], which is exposed at the surface only in the upper catchment. This type of soil has low permeability, resulting in faster surface water flow and high runoff, potentially contributing to exacerbating the flooding, specifically to the high-velocity-bound flooding condition. Across the mid-catchment location, the bedrock is overlain by sand, silt, mud, and a gravelly ferrosol with Quaternary alluvium and lacustrine soil (with a clay loam to clay texture) near creek locations, as shown in Figure 9. These types of soil contribute to increasing the probability and intensity of flooding by allowing water to infiltrate and saturate the surrounding soil. Bedrock in the lowermost location of this catchment is overlain by Holocene clay, silt, sand, estuarine, and deltaic deposits. Furthermore, initial and continuous losses accounting for how soil and plants enable infiltration and evaporation, associated with these soil types, were obtained from the Queensland Government website.

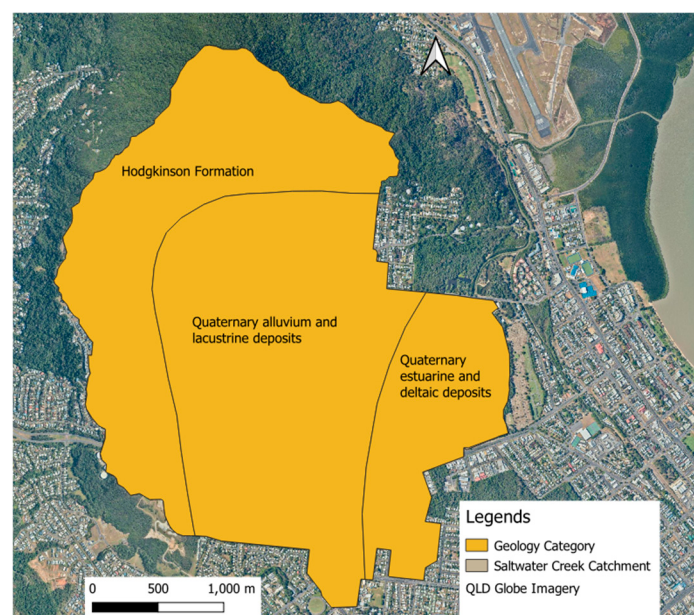


Figure 9. Geological and soil type distributions in Saltwater Creek catchment.

2.2.9. Climate Change Data

The climate change scenarios and data were sourced from the Queensland Government Long Paddock website [39], which contains regional maps illustrating the projected mean temperature for each local area in Queensland. These temperature data were used to calculate interim climate change factors, as shown in Figure 10. The method for such calculation was explained in [40], published by a similar group of authors. The ICCF data calculated was used in the Storm injector tool to generate rainfall design events under current and climate change scenarios.

2.3. Method

Figure 11 presents the research methods adopted for this study, showing each step adopted for the hydrological and hydrodynamic model setup, calibration, validation, and simulation scenarios.

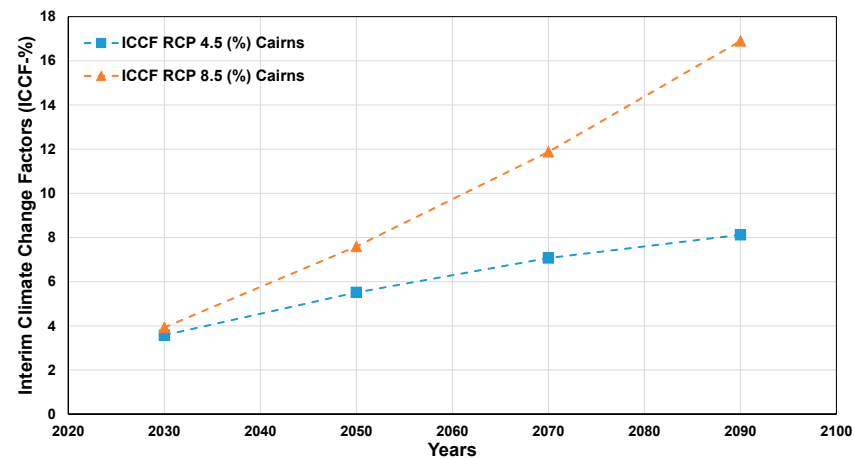


Figure 10. Calculated interim climate change factors (ICCFs) based on the temperature data from Long Paddock for the Saltwater Creek catchment, used for simulating climate change impact.

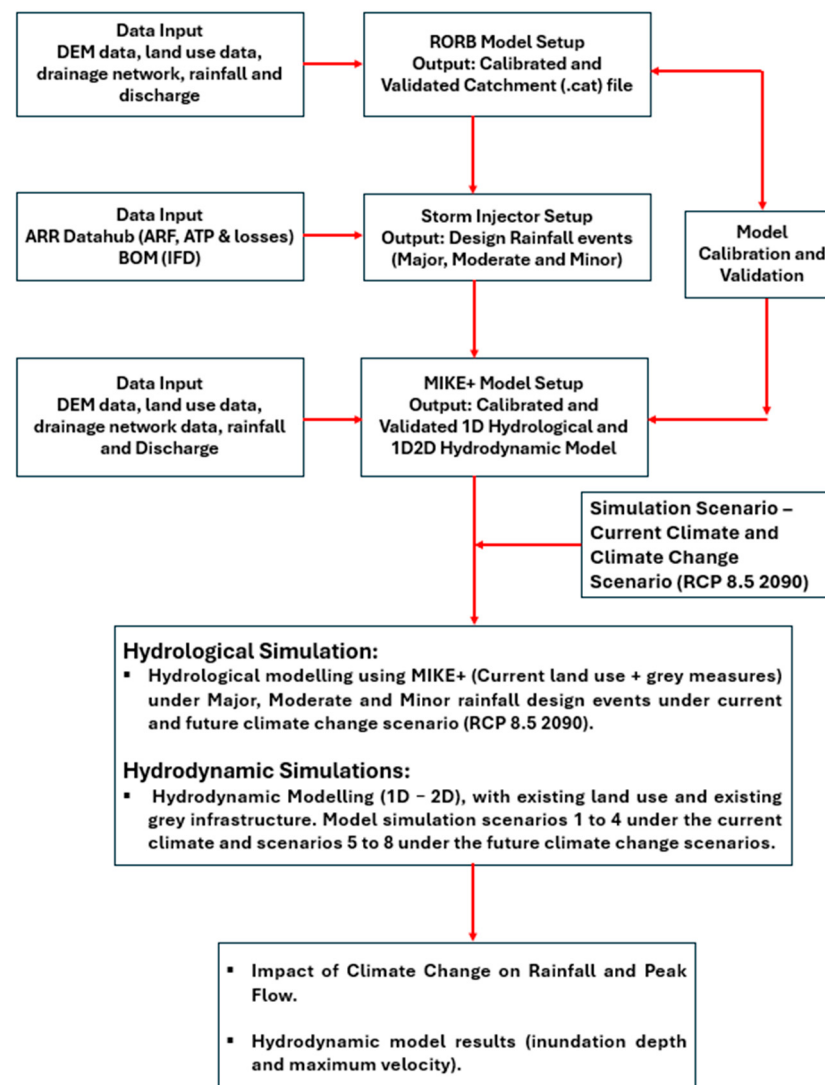


Figure 11. Flood modelling approach.

2.3.1. Rainfall Runoff Model Selection and Setup

RORB was selected for hydrological simulation due to its free availability and wide range of applications in Australian catchments [41]. This tool is a streamflow routing

program that calculates hydrographs from rainfall and subtracts losses from rainfall due to evapotranspiration and infiltration to generate runoff [42]. The RORB model delineated and developed a catchment with 14 sub-catchments from DEM for further modelling work (Figure 12).

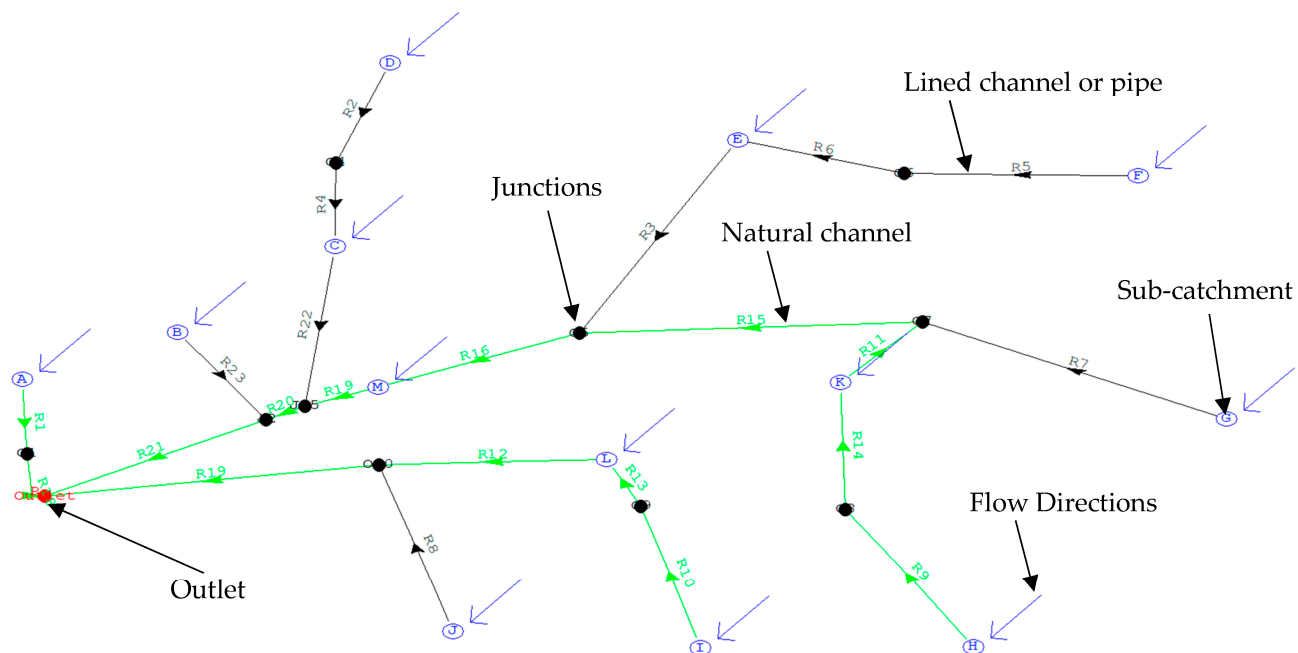


Figure 12. Saltwater Creek RORB catchment (.cat) file setup with key features.

2.3.2. Hydrodynamic Model Setup

The MIKE+ hydrodynamic model was adopted in this study due to its wide range of global use in industry and academia, its integrated platform capacity to conduct both hydrological and hydrodynamic simulations, and its coupling capability for 1D and 2D geometry [43–45]. MIKE+ was the choice over other public and commercial models, such as HEC-RAS 2D, Delft3D, and TUFLOW, for several reasons. One of the major reasons for selecting this tool was its integrated single platform for performing hydrological, hydrodynamic, and water-sensitive urban design (WSUD) modelling. In addition, DHI offered a free student version of the tool with unlimited capacity, while some other commercial versions were expensive and out of range of our research budget.

The catchment area was delineated by the MIKE+ automatic tools and further refined through manual delineation, taking into account the catchment contours, road network, and underground drainage. At the final stage, 141 sub-catchments were finalised for hydrological simulation using the kinematic wave method, with sub-catchments ranging in size from 0.013 to 0.35 km².

The MIKE+ collection system (CS) platform was utilised to define the pipe networks, inlets, manholes, culverts, and canals at this study site. Then, each catchment was coupled to the CS system, illustrating the flow received by nodes. MIKE+ uses MIKE11, a 1D hydrodynamic model that solves the 1D shallow water equations and Saint-Venant equations to simulate unsteady flow in these networks [44]. Additionally, the 2D overland flow model, which used the MIKE 21 hydrodynamic model platform within the model, was employed to develop a rectangular grid with a spatial resolution of 1 m × 1 m. Both models can be linked with each other through the boundary using the weir formula with the crest level.

The catchment boundary condition variable was defined using the design rainfall time series. Additionally, 2D water level time series with tidal time series levels are defined at the boundary location where the creek and ocean interactions occur.

The initial water level condition was defined as varying in the domain of the wetlands, creeks, and river channels.

The model coupling platform within MIKE+ allows for hydrodynamic interaction between surface water (2D) and subsurface stormwater (1D) domains (Figure 13). The MIKE+ coupling platform enables the coupling of two domains using inlets, manholes, and outlets.

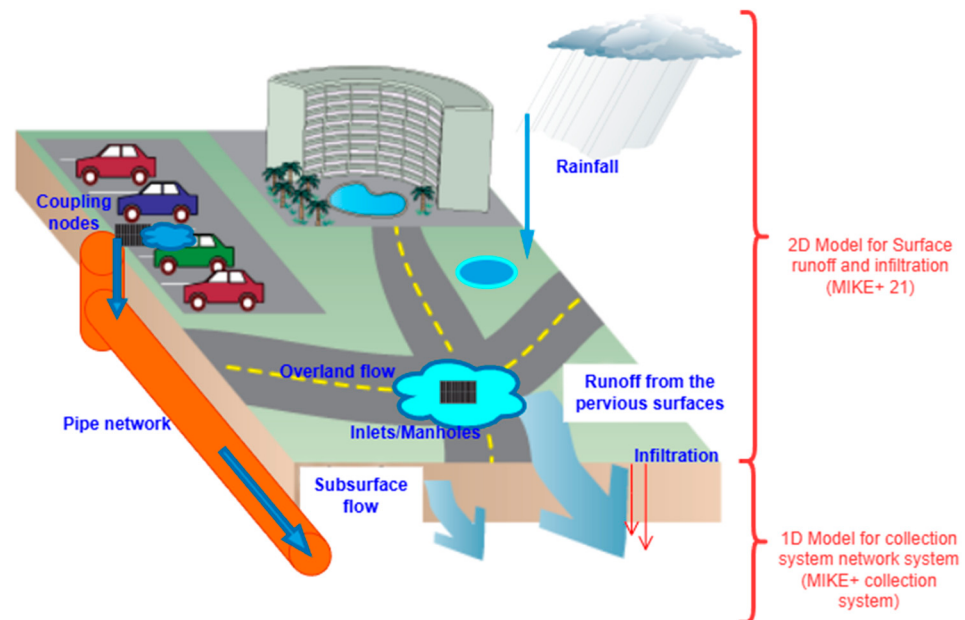


Figure 13. Schematic setup of the MIKE+ model (modified and adapted from [46]).

2.3.3. Rainfall Design Events

Storm Injector, commercial software [47], was used to develop rainfall design events for flood modelling under current and future climate change scenarios, along with the required results that link RORB and MIKE+.

This tool features an integrated platform for managing hydrologic model catchment files created in RORB. The catchment files from the RORB model are populated with storm files directly extracted from the ARR data hub, as well as the IFD curve from the BOM. This data was required to generate peak flow and critical time-to-peak flow hydrographs, among several temporal pattern combinations, as recommended by the ARR guideline for flood modelling in the Australian context. This tool also has additional capacity to incorporate climate change scenarios and calculate design events under future climate scenarios.

2.3.4. Calibration and Validation Event Selection

Model calibration and validation were conducted to evaluate the comparative performance of simulated results against measured flow. The approach identified and described in the AAR (2019) was adopted for selecting events for calibration and validation [48].

Storm selection criteria were based on cumulative storm depth, maximum duration, antecedent rainfall, end of rainfall, flow, and burst duration. Additional criteria for the discharge range were also considered for further simplification based on the measured water level during this study. Discharges greater than 40 m³/s were regarded as major, 20 to 40 m³/s as moderate, and less than 20 m³/s as minor events. We selected six events for model calibration and three events for validation, as described in Table 1.

Table 1. Rainfall event characteristics adopted for model calibration and validation.

Events	Types	Rainfall Depth (mm)	Rainfall Duration (Hours)	Peak Flow (m ³ /s)	Remarks
Calibration Events					
29 January 2020	Major	154	21	46	
17 December 2023	Major	472	81	56	Tropical Cyclone Jasper, 13–18 December 2023
4 April 2019	Moderate	138	30	30	
13 January 2024	Moderate	71	17	24	
28 January 2020	Minor	32	16	9	
27 February 2020	Minor	59	15	18	
Validation Events					
24 March 2021	Major	110	24	51	Tropical Cyclone Niran
25 February 2020	Moderate	57	14	29	
22 February 2020	Minor	56	14	16	

2.3.5. Model Calibration and Validation

During model calibration and validation, to test the hydrological model performance, several goodness-of-fit criteria, including Nash–Sutcliffe efficiency (NSE), ratio of root mean square error (RMSE) to the standard deviation of the observation (RSR), Per Cent Bias (PBIAS), peak, and volume [49], were used to calibrate and validate the model. The NSE value ranges from 1 to $-\infty$; NSE = 1 indicates perfect agreement between modelled and observed data; NSE = 0 means the mean of the observed data is as accurate as the model predictions. RMSE is the mean difference between a statistical model's predicted values and measured values. In addition, the PBIAS parameter was used to measure the tendency of modelled results to be below or above the measured results. Finally, the peak flow/total volume error is also assessed, as peak flow is a hydrological parameter and a critical input for hydraulic design [30].

2.3.6. Methods for Uncertainty Reduction

To reduce the uncertainty associated with model performance due to a short data period, this study adopted an approach of model calibration and validation, which was based on the relative comparison of simulated and measured outflow hydrographs. The selection of events during model calibration and validation was performed in such a way as to reduce bias. For example, the range of major to minor flooding events was selected for this process. Similar sets of events were selected and tested under a range of scenarios during validation. Although short periods of data introduce challenges in predicting extreme events, such as 1% AEP, luckily, two major cyclonic events (Tropical Cyclone Jasper, 13–18 December 2023, and Tropical Cyclone Niran, 1 March 2021) happened during this monitoring period, so one of the events could be selected for calibration and the other then used for validation. Other ranges of events were also assessed in this way, providing us with confidence that, even with a short period of data, the modelling outcomes are valid.

2.3.7. Simulated Scenarios

MIKE+ hydrological modelling and hydrodynamic compound modelling scenarios were conducted to assess the impact (Table 2). The hydrological model was used to simulate three design rainfall events under the current climate (CC) and a future climate change scenario (RCP 8.5, 2090). In addition, hydrodynamic simulation scenarios 1 to 4 represent compound flooding under CC scenarios, while scenarios 5 to 8 represent the corresponding

compound flooding under future climate change scenarios with RCP 8.5 in 2090. The extreme results are presented in Sections 3 and 4.

Table 2. MIKE+ model simulation scenario combinations.

Scenario	Description
Hydrological Simulation Scenarios	
Rainfall	Major, moderate, and minor
Climate Change	Current climate (CC) and RCP 8.5
Hydrodynamic Simulation Scenarios	
Scenario 1 (S1)	Major rainfall design event under CC + high astronomical event time series (measured tidal time series)
Scenario 2 (S2)	Major rainfall design event under CC + minor tidal level (measured tidal time series)
Scenario 3 (S3)	Moderate rainfall design event under CC + minor tidal level (measured tidal time series)
Scenario 4 (S4)	Moderate rainfall design event under CC + major tidal level (measured tidal time series)
Scenario 5 (S5)	Major rainfall design event RCP 8.5 2090 + high astronomical tidal event time series (measured time series) + SLR (80 cm) + surge value (20 cm)
Scenario 6 (S6)	Major rainfall design event RCP 8.5 2090 + minor tidal level (measured tidal time series) + sea level (80 cm) + surge value (20 cm)
Scenario 7 (S7)	Moderate rainfall design event RCP 8.5 2090 + minor tidal level (measured tidal time series) + sea level (80 cm) + surge value (20 cm)
Scenario 8 (S8)	Moderate rainfall event RCP 8.5 2090 + major tidal level (measured tidal time series) + sea level (80 cm) + surge value (20 cm)

3. Results

3.1. Hydrological Model Calibration/Validation

The simulated and observed stream flows for Saltwater Creek at the Greenslopes Street outlet were used during the calibration and validation. A total of six events were selected for model calibration, and three events were chosen for validation. The calibrated and validated results are summarised in Table 3. The models demonstrated strong overall performance during calibration, with NSE values for calibration periods at the Saltwater Creek outlet ranging from 0.59 to 0.81 and 0.5 to 0.92, respectively, for the RORB and MIKE+ models. Similarly, the validation NSE results for RORB and MIKE+ range from 0.73 to 0.95 and 0.57 to 0.85, respectively. The NSE results range from good to very good performance ratings, indicating good overall model performance [30,49]. Since the events considered for model calibration and validation range from major to minor, the model can reliably estimate a broad range of flow conditions. Both models exhibited low peak flow estimation errors ($\pm 5\%$) for most events, indicating strong alignment with observed peak flows.

Table 3. RORB and MIKE+ hydrological model calibration and validation results.

RORB/MIKE+ Model Calibration Results											
Events	Type	PF Error, m ³ /s		NSE		RMSE		R ²		RSR	
		RORB	MIKE+	RORB	MIKE+	RORB	MIKE+	RORB	MIKE+	RORB	MIKE+
29 January 2020	Major	0.00	−0.07	0.79	0.85	7.01	5.9	0.89	0.95	0.46	0.39
17 December 2023	Major	2.98	−0.03	0.81	0.76	8.52	9.5	0.91	0.93	0.44	0.49
4 April 2019	Moderate	5.14	−0.04	0.78	0.73	3.85	5.8	0.89	0.89	0.48	0.7
13 January 2024	Moderate	3.65	−0.01	0.77	0.89	3.37	2.4	0.91	0.96	0.56	0.34
28 January 2020	Minor	1.33	0	0.77	0.5	1.38	2.1	0.89	0.83	0.48	0.71
27 February 2020	Minor	0.48	0	0.59	0.92	2.77	1.6	0.92	0.94	0.94	0.37
RORB/MIKE+ Model Validation Results											
24 March 2021	Major	−0.43	−0.04	0.95	0.8	2.9	6.1	0.98	0.93	0.22	0.44
25 February 2020	Moderate	4.65	−0.022	0.75	0.85	4.1	3.2	0.90	0.96	0.5	0.39
22 February 2020	Minor	3.69	−0.27	0.73	0.57	2.9	3.6	0.89	0.9	0.52	0.66

3.2. Model Sensitivity Analysis

Flood models are highly sensitive to both spatial and temporal resolution of input data. To address such issues, sensitivity analysis was conducted during this research work. A coarse grid size results in higher errors with slower convergence leading to inaccurate flow paths and instability in the model. At the same time, a grid that is too fine requires a more powerful computer to run simulations for an extended period; however, this results in better flood predictions of the rainfall runoff process. To address both limitations, optimal grid size sensitivity testing was conducted. The grid size of the model was set to 1 m × 1 m, 2 m × 2 m, 3 m × 3 m, and 4 m × 4 m. Sensitivity testing determined that an optimal grid size was 2 m × 2 m. The 1 m × 1 m grid required 24 h of synthetic testing. In contrast, other grid sizes yielded a significant error in assigning surface elevation to the 1D2D domain-coupled locations. During some simulations, the elevation difference between the two coupled domains was up to 10 m, exceeding the threshold limit and in turn impacting the model stability, flow inundation, and runoff exchange between the domains.

In addition, the sensitivity testing time-step selection for hydrodynamic modelling using MIKE+ determines the stability of the modelling process. These issues are generally caused when the temporal resolution of models misrepresents the timing of peak flow. The optimal step selection requires updating the equation governing fluid flow to provide detailed flow characteristics. A step that is too large increases numerical instability and reduces accuracy, whereas a step that is too small requires a substantial increase in computing time. This model identified a 1 s time step for 2D overland flow as an optimal time step and 60 s for the surface runoff models.

The low-order fast algorithm was selected over the high-order, more accurate algorithm due to the higher time requirement for simulations using the latter. The wetting and drying depths must be considered to capture the inundation depth within the catchment. A 2 mm wetting depth and 3 mm drying depth were identified as appropriate during this sensitivity testing. The small drying and wetting depths capture the water level in a low-lying area.

3.3. Climate Change Impact on Hydrology

The alteration in rainfall depth under major, moderate, and minor design events, as well as climate change scenarios such as CC and RCP 8.5, is presented in Table 4. The results show an increase in rainfall depth when comparing CC and RCP 8.5 for 2090. Meanwhile,

the major and moderate events showed a 14% increase in rainfall depth, while minor events showed a 19% increase, during RCP 8.5 2090 compared to the CC.

Table 4. Rainfall and peak flow alteration for design events using the MIKE+ hydrological model.

Scenario	Total Rainfall Depth (mm)		
	Minor	Moderate	Major
CC	86	136	334
RCP 8.5 2090	106	159	390
Scenario	Peak Flow (m ³ /s)		
	Minor	Moderate	Major
CC	35	54	99
RCP 8.5 2090	42	67	125

Similarly, the peak flow increment during RCP 8.5 2090 ranges from 17% to 21% for rainfall design events when compared to the CC. All the modelled rainfall events resulted in a significant increase in rainfall and peak flow, implying a potential severe flooding risk during future climate scenarios. In conclusion, the results suggest that climate change has a disproportionately greater impact on minor hydrological extremes compared to major events.

3.4. Hydrodynamic Model Result

3.4.1. Inundation Depth

The compound effects of rainfall, tidal level, and SLR under current and future climate scenarios were examined. The flood maps show the altered maximum water depth, flooding hotspots, flood extent area, and critical grey measures (Figure 14). S1 represents flood maps that illustrate the compound effects under current climatic conditions, and S5 represents corresponding combination scenarios under climate change (RCP 8.5, 2090).

Under the CC scenario, the study site has an inundation proportion of 3% to 18% of the catchment area. The maximum inundation occurs when major rainfall coincides with a high tidal level, that is, during S1. Different locations within the catchment exhibited varying maximum inundation depths, ranging from 0 to 4.6 m (S1). The maximum water level increase was observed along the flow paths of Saltwater Creek and its tributaries. The inundation depth was further distributed along the low-lying areas and for 50 m on either side of the Saltwater Creek corridor.

Under the extreme climate change scenario of RCP 8.5 for 2090, modelling suggests inundation areas of 5% to 25%, as illustrated in Figure 15. Due to the compounding effects, an additional 2% to 7% of the area is expected to be affected by future flooding compared to the CC S1 scenario. In addition, the maximum water level ranges from 0 to 5.6 m (S5). Under this climate change scenario, the observed inundation depth increased by 15% to 28% compared to CC S1. As a result of climate change, the maximum water level variation has expanded from the creek to urban areas, reaching up to 80 m on either side of the Saltwater Creek corridor.

The flooding hotspots are primarily concentrated in low-lying areas of the study sites, specifically those at an elevation of <4 m AHD. The eastern sub-catchments are continuously flooded under most of the compound scenarios tested for this study. However, localised flooding hotspots due to overland flooding were also observed at the northern, south-western, and western upstream urban and road areas. Most of these hotspots were due to the hydraulic insufficiency of grey measures such as inlets, pipes, manholes, and culverts. Most culverts experience high overflow, inundating roadside areas and contributing to floods that propagate to the nearest urban area.

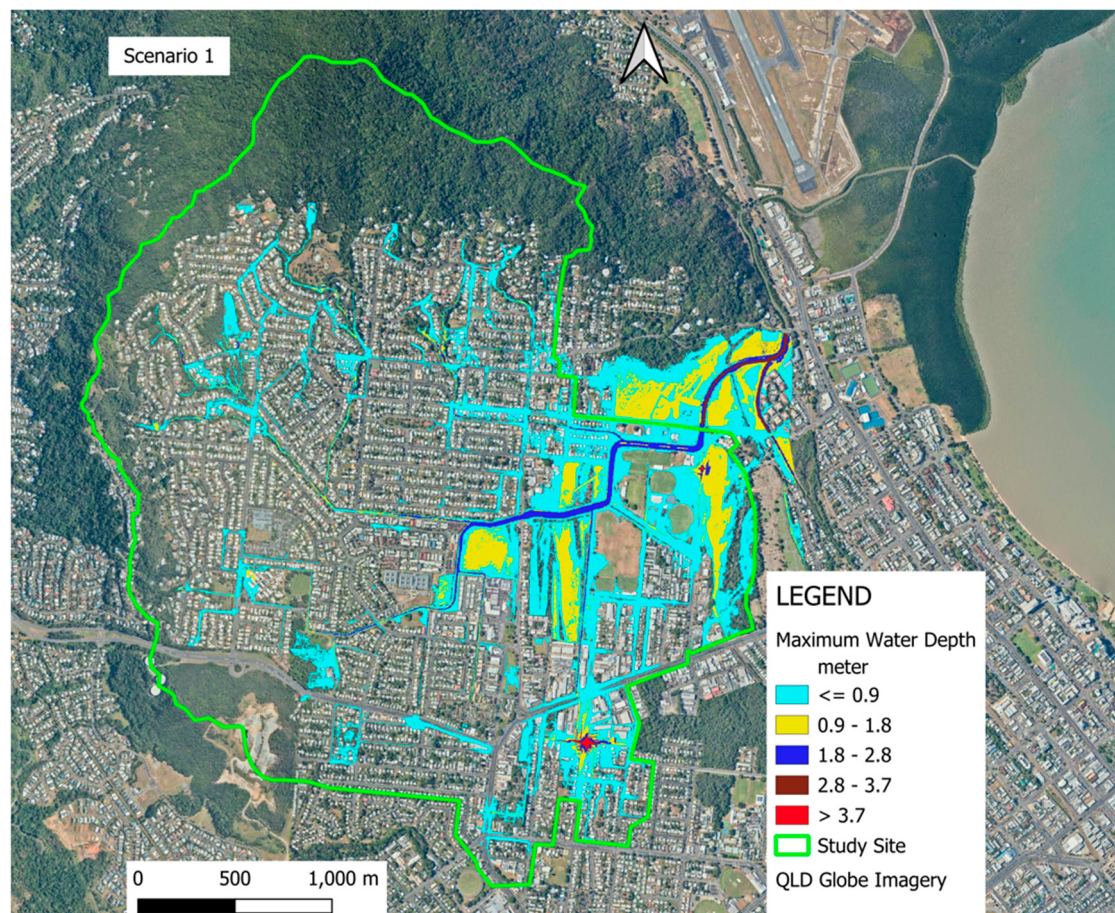


Figure 14. Compound flooding events, inundation depth, maximum water level variations, and flood extent areas under CC (Scenario 1 (extreme scenario)).

The central part of the catchment experienced minimal flooding. This may be due to well-drained steeper topography, which will likely reduce maximum overland flow and flood inundation. However, with the presence of several inlets, the pipe network in this catchment allows the flow to occur in both directions (forward and backward) depending on the hydraulic gradient. On the other hand, the tailwater level difference at the outlet location of the pipe networks determines the outflow or inflow conditions from the pipe network to the natural drainage. Low tailwater conditions can enhance the effectiveness of grey measures that intercept runoff from roadside and urban areas, which are then discharged into creeks and support downstream flow, thereby reducing the likelihood of overland flooding. In contrast, if the tailwater level is high, flow from the pipe outlet is constrained, leading to higher surface runoff and an increase in either the inundation depth or the flood extent area. The numerous outlets in an urban area can therefore have a ripple effect, transferring flooding conditions to different catchment locations, even farther from the actual sources. This study utilised interpolated data, referencing the outlet water level data from the council sensor, to determine the tailwater condition. The lack of precise tailwater levels for the pipe network outlet locations likely impacted the flooding results in the mid-catchment of this study. The tailwater level of the pipe network outlet controls the runoff interception and transportation mechanism through inlets and the pipe network.

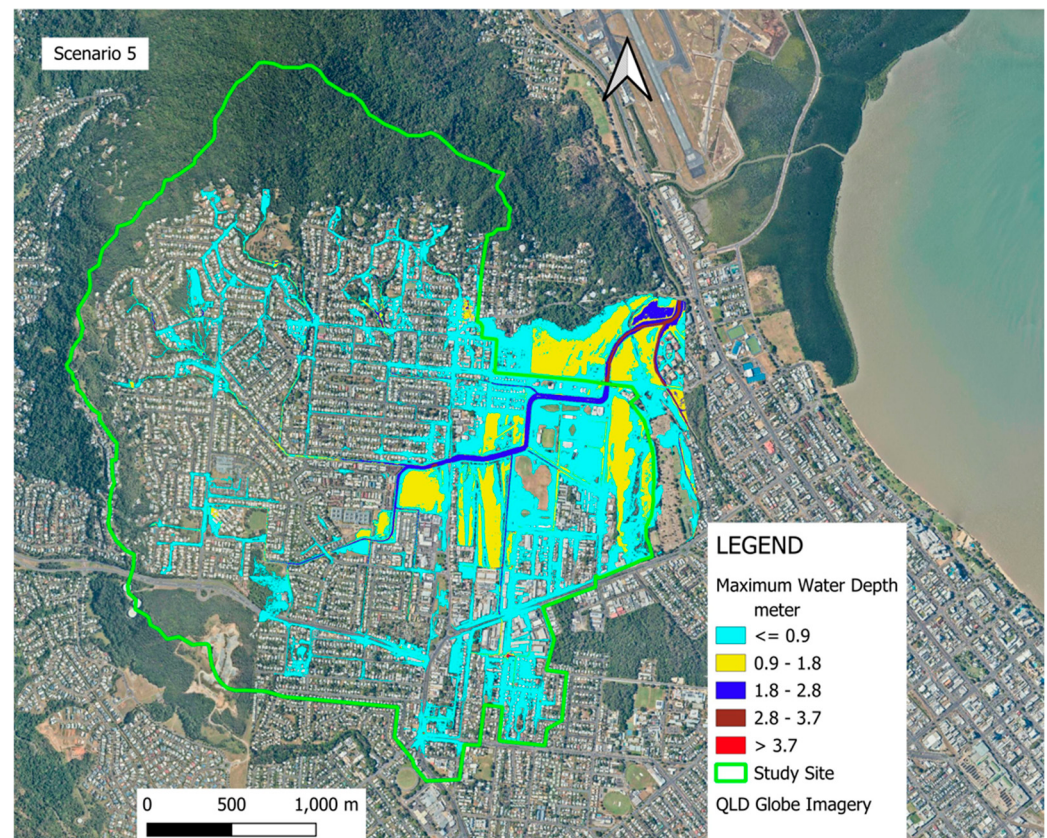


Figure 15. Compound flooding events, inundation depth, maximum water level variations, and flood extent area under a future climate scenario (Scenario 5, extreme scenario under RCP 8.5 2090).

3.4.2. Velocity Alterations

Velocity is the least discussed parameter in analyses such as those performed for this study [50], due to its high computational demands. However, it can provide valuable insights into the kinetic energy associated with the flow and the potential damage caused by moving water. This information is crucial for evaluating flood hazards and developing effective flood mitigation strategies, including inlets, pipe networks, culverts, and bridges.

The maximum velocity alteration under S1 during CC scenarios is presented in Figure 16. A velocity of 0.3 m/s was adopted as the minimum value for all scenarios. The velocities range from 0.3 to 4 m/s; however, the variation in velocity depends on the sources of combining factors that govern the flow conditions. Scenario 1 showed maximum velocity variations.

The extreme velocity values were concentrated along the central line of the flow path, specifically within the creek itself. The maximum velocity, observed at approximately 4 m/s, was recorded in the uppermost part of the catchment, correlated with the steepest elevation gradient in the catchment. However, the southern and northern sub-catchments, near the outlet of the concrete drain, also experienced high velocities. Although these sub-catchments do not undergo significant slope changes, the runoff discharged to the concrete channel from the pipe network exhibited a high velocity. In contrast, the low-lying area near the main catchment channel and the overland flow experienced minimal velocities.

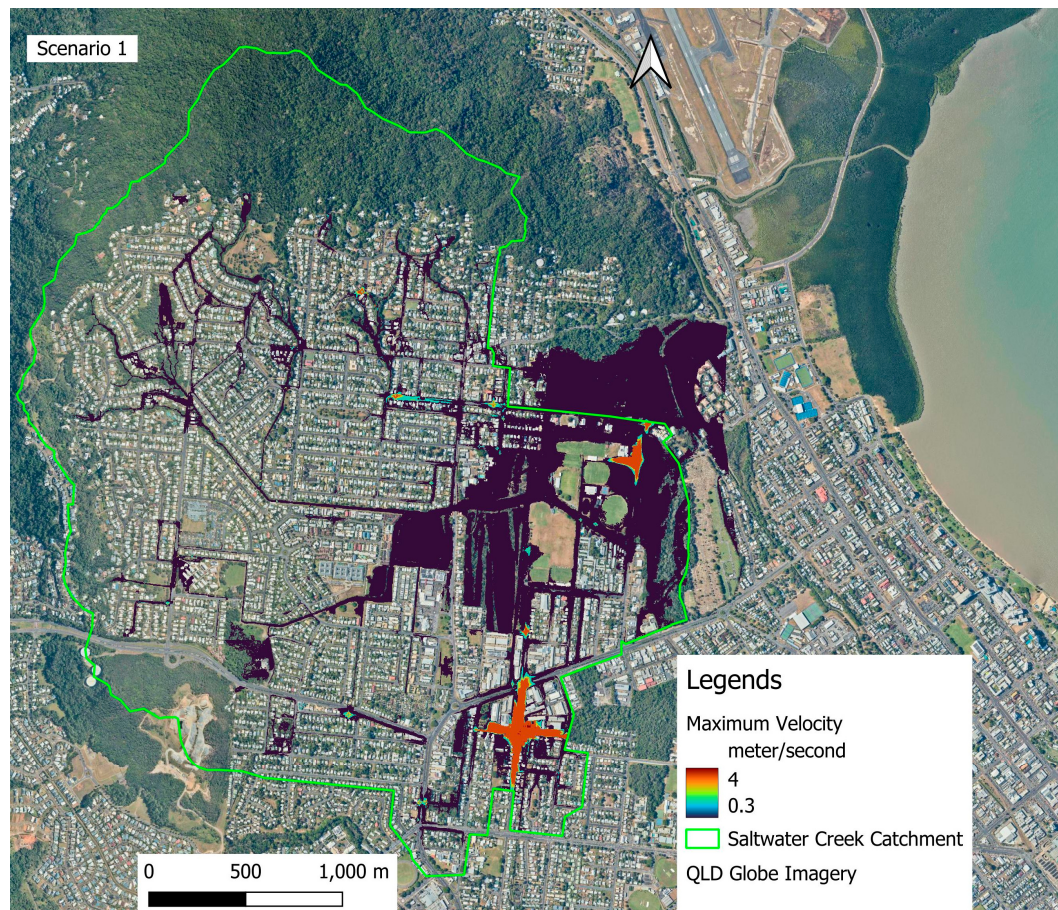


Figure 16. Compound flooding events, maximum velocity variations under CC (Scenario 1 (extreme scenario)).

The maximum velocity alteration from S5 during future climate change scenarios is presented in Figure 17. The velocity ranges from 0.3 to 4 m/s, depending on the combination of factors governing the flow conditions. The maximum velocity alteration under climate change scenarios was observed during S5, with an extended area experiencing higher velocity within the catchment.

Maximum alterations in velocity were observed at the outlet location of the pipe network connecting the creek and the overland flow. Additionally, drainage locations, such as the entry and exit points of culverts, also exhibited the maximum alteration in flow velocity. This information can provide valuable insights into the condition of the pipe or drainage flow. Generally, piped flow can increase peak flow at the downstream or outlet location, potentially resulting in flash flooding. The flow velocity data from the drainage network can be used to evaluate the safety of structures against the kinetic force associated with the flow.

Under RCP 8.5 2090 scenarios, a number of locations within the catchment experience maximum velocity compared to S1 scenarios. The north side and south downstream locations experienced maximum velocities, despite topography limiting the flow velocity under the RCP 8.5 2090 scenario. Maximum velocities exceeding 4 m/s at these locations can sweep away humans, vehicles, and buildings. In addition to the inundation in the low-lying areas of this catchment, the risk of high velocity is another critical aspect.

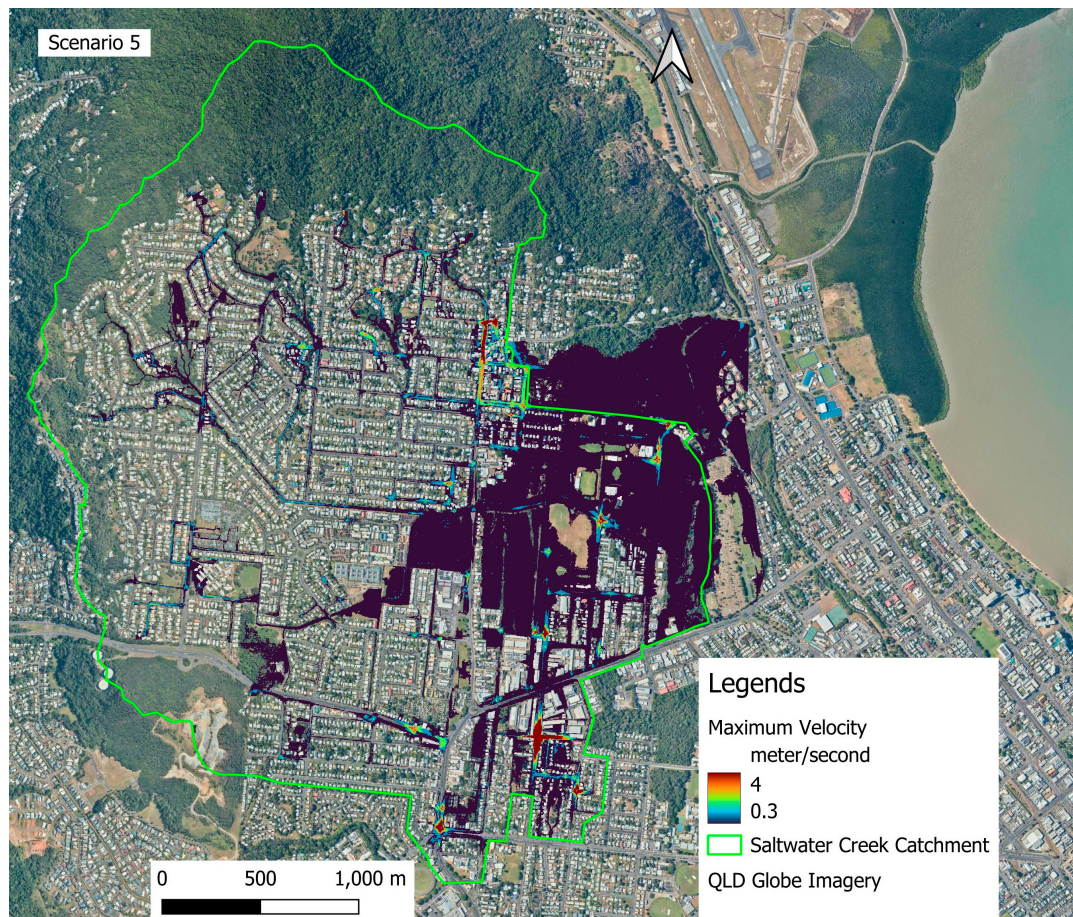


Figure 17. Compound flooding events, maximum velocity variations under future climate change (extreme scenario under RCP 8.5 2090) scenario (S5).

4. Discussion

This study aims to understand the scale and impact of compound flooding events governed by extreme rainfall, tidal level, and sea level rise under current and future climate scenarios at this study site.

4.1. Modelling Performance Results

Model performance and its results are dependent on several factors, including the spatial and temporal scale of data, as well as tool integrations.

The results generated during this study were compared with regional modelling results [51]. The observational comparative assessment of 1% AEP results from the MIKE+ model maps and the baseline inundation maps reveals several areas of agreement with known flood hotspots and inundated areas within the catchments. Still, there are several locations of disagreement between these two results. After the assessment, the regional model may have a higher probability of overestimating the flood extent area compared to the current study, as the regional model has overgeneralised the parameters adopted for hydrodynamic modelling. The current model has utilised the best available data to establish a model that accurately represents the condition of this catchment.

Elevated ocean levels can be caused by a range of processes, including tides, tidal anomalies, waves, wind setup, and, in the future, sea level rise. These events have a significant role in flood modelling in coastal catchments, although a simple model uses static ocean water level based on long-term tidal gauges, while for in-depth analysis, consideration of the dynamic nature of coastal water levels is required [52]. To improve the

model results, this study has used the tidal time series that represent the dynamic nature of the coastal flow conditions.

Another important aspect of modelling performance is dependent on the tailwater conditions of the outlet pipe network. The water level condition was interpolated due to limited known data. Although interpolation of tailwater conditions is highly dependent on the initial quality of data, the dynamic nature of tailwater conditions has a severe impact on the flooding predictions in the catchments.

4.2. Compounding Modelling: Philosophical to Practical Approach

Understanding of compound events lacks complete philosophical consistency; different institutions, such as the Intergovernmental Panel on Climate Change (IPCC) [53], Australian rainfall runoff (ARR) [54,55], and Scottish guidelines [56] have defined such events in different ways, which limits understanding and application [8].

Through practical modelling work, several approaches have been adopted for simulation purposes, including simulating historical extreme events, probabilistic approaches (joint statistical methods), hybrid frameworks (statistical sampling and numerical modelling), and a fully coupled model able to solve hydrology and ocean dynamics simultaneously [7–9,18,19,57–59]. Compound flood modelling is a complex process, particularly for locations with limited data, resulting in scale mismatches and statistical uncertainty.

The current study adopted a multivariate scenario-based approach, utilising a 1D2D hydrodynamic coupled model driven by rainfall (from major to minor events) resulting in pluvial flooding, with additional data for 2D surface flow, river routing, high- and low-tide time series, and urban drainage systems. This approach provided an advantage in extensively detailing the interaction between different flow domains, as well as scenario combinations. However, this method requires significant data for model setup and a time-consuming process for calibration and validation. Coupling the 1D and 2D geometries is a challenging aspect of this approach. The approach likely includes minor errors in setting boundary conditions, which can propagate and affect numerical stability, resulting in a significant reduction in model accuracy over time. Statistical joint probability methods of compound flooding modelling were not adopted during this study due to its short data period (6 years), which can result in high statistical uncertainty, leading to underestimation of extremes and unstable fits [60,61].

4.3. Compounding Effects

The results presented here have several implications, including for the efficacy of existing flood mitigation measures, the future need for flood mitigation measures, decision-making processes for selecting mitigation approaches, and investment decisions. Each year, flooding events affect numerous locations in this catchment, and complete mitigation of the flooding problem is impractical. However, being prepared, informed, and proactive during such events is essential to minimise the risk of flooding and associated economic and human losses.

The existing grey measures intercept runoff and often function under pressured flow conditions during major events, increasing the discharge rate at the outlet. This can lead to flash flooding at downstream locations. Besides increasing the severity of such events, grey measures can also increase flood risk at the upstream end of the catchments. Grey measures are designed to enable flow in the downstream direction but can also induce backflow, depending on the tailwater conditions. During compound flooding events, the higher water levels at the outlet locations reduce the functionality of inlets, propagating pluvial flooding. Specifically, major rainfall events combined with king tides can result in excessive economic losses due to inundation and damage to vehicles and homes.

Low-lying urban areas are critically exposed to flood risks in the study catchment. This flooding generally has a low flow rate but high water depth, resulting in an inundation problem. Notably, areas with minimal gradient and locations with backflow, such as those experiencing tidal flow, frequently encounter these problems. On the other hand, the low-lying areas with constrained drainage capacity still experienced high-velocity flow. However, the upstream portions of this catchment experience high-velocity flow flood risk, driven by steep gradients. Although the upstream locations of this catchment's topography are not subject to significant inundation, high flow velocities are predicted at such locations. High-velocity flow can sweep away vehicles, houses, infrastructure, and humans, as well as scour the soil along the flow path.

The results discussed in this research, such as maximum water level variation and maximum velocity, have significant implications for risk assessment. Most flood studies primarily focus on inundation depth when talking about flood risk. However, this is insufficient to holistically assess flood risk because it does not account for the complexity of flooding within the catchment and the energy associated with the flow. The high flow velocity at the upstream end of the catchment not only drains runoff to the downstream site in a short time but also increases flash flood risk. This high energy is sufficient to wash away people and vehicles on roads and in drainage lines. On the other hand, with an increment in flow velocity, there is sufficient energy to erode property areas with attendant economic losses. The high flow velocity can also initiate and increase the erosion along the flow path and carry natural soil downstream, and this soil then settles in the stream path and drainage system, such as in culverts, eventually contributing to increasing the flood extent area. The study observed a strong correlation between the flow velocity and structural damage to road infrastructure, while flood depth and energy head exert more influence on structural damage to residential buildings [62]. Therefore, to minimise such problems, the related velocity, energy head, and depth should be considered in the coming days for assessment. Thus, flood mitigation approaches also need to be thought out in a way that reduces all parameter impacts during the flooding period.

Besides flood mitigation, grey measures such as inlets, manholes, and culverts are critical locations for propagating the flooding problem within a catchment. Such locations are potentially compromised by uncertainty in their effectiveness for flow interception and conveyance under climate change. Such infrastructure requires continuous improvement in hydraulic capacity, which can be achieved through redesign and rehabilitation. These grey measures can be redesigned by considering the impact of climate change on flood mitigation design [63,64]. Based on these results, grey measures can be rehabilitated; however, this is a complex construction activity that is costly and time-consuming. Therefore, an in-depth study should be undertaken before this approach is adopted, and possible alternative options should be explored with an economic evaluation before any planning measures are implemented.

This study presents the results as an inundation flood map showing depth and velocity separately. However, results are separately presented to enable discussion of the importance of velocity in flood results, which is often ignored. The study site is narrow, and runoff from upstream moves rapidly downward in a short time, interacting with additional tidal inflows toward the outflow of the catchment. Many coastal cities have similar types of topography, and this requires local-level assessment to mitigate the flood risk; the tailored approaches of assessment and mitigation might not be suitable in such cases.

4.4. Implication of Compound Flooding

The results indicate that the flooding condition of this catchment is projected to worsen in the future. The current results were solely based on the impact of climate change on the

increment in flow conditions; however, this is also attributed to other factors, such as land use change. During this study, land use change was kept constant during future climate change scenarios to understand its sole effect only; however, this can have an additional impact, increasing localised flooding challenges. This means that the flooding scenarios can be more serious than what we have seen in the results.

The projected flooding problem is expected to continue in the future; therefore, understanding the limitations of existing measures and seeking alternative novel technologies, such as nature-based solutions, are key aspects that authorities need to explore. This is particularly the case for the future climate change scenarios, which suggest high uncertainty in the amount of runoff received by the grey measures. Upgrading, adding, and rehabilitating grey measures, which have a fixed capacity to accommodate runoff, might require major expansion at considerable cost.

So far, under our acknowledgement, in tropical catchments, so few studies are conducted that an exact comparative assessment was difficult, even though other catchments in this climatic zone might have experienced severe flooding conditions compared to this catchment. However, these have not been reported, which makes it difficult to understand the exact scenario of compound flooding in other tropical catchments. However, it is often regularly reported that these flooding conditions occur in other climatic zone catchments [23–25].

The frequent occurrence of similar types of events challenges administrative bodies to review their current approach to mitigation approaches and resources invested to mitigate flood risk. The current approach of sole grey measures cannot deal with altering uncertain flooding conditions; to deal with such challenges, integrated multifunctional systems with a holistic view of urban and coastal systems, such as WSUD, are necessary.

5. Limitations of the Study

The results obtained from any modelling approaches must take into account methodological constraints and the uncertainties associated with data coverage and quality. This study focused on a number of stressors that influence major flooding in a small wet tropical urban catchment. Climate change impacts rainfall, SLR, and tidal rise, and their combined effects have been considered in the simulations. A significant assumption in this modelling lies in using existing land use for current and future climate change (RCP 8.5 2090). Although this assumption does not have an impact on current climate scenarios, it has a significant impact on future climate change scenarios, limiting the real case flow scenarios.

This assumption was made to understand the climate-driven impact of flooding under the existing land use. Urbanisation alterations have several effects associated with changing the microclimate conditions and increasing the area of impervious surfaces, significantly impacting overland flow generation and the increase in inundated regions under future climate change conditions. Thus, further urbanisation can considerably increase the inundated area compared to the current results obtained from the model. An account of future changes other than those in response to climate change has not been included.

Additionally, the drainage network model was accurately configured in terms of its position, types, and sizes of structures, as well as flow directions, based on the data provided by the CRC. Several field visits to the site were also conducted to understand the exact conditions and cross-validate the provided data. However, several input values for these grey measures are missing and were interpolated from the nearest available data. For example, several pipe network invert levels were interpolated, considering the nearest available data. This can also cause flooding problems in specific catchments or localised

areas. If more accurate data became available, the results presented in this study might be altered and improved.

Furthermore, the limited availability of high-resolution, long-term data has hindered the few studies conducted in tropical cities regarding compound flood events. However, long-term data does not always ensure an improvement in the modelling results, which are largely dependent on the quality of data. The positive aspects of this study include the availability of data layers for a 2021 high-resolution DEM, drainage networks, advanced computational tools, and powerful computers, along with software such as MIKE+. This contributed to the successful modelling of the complex compound flooding problem in the study catchment. Nevertheless, the data used in flood modelling (rainfall, tidal, and water levels) only covers six years. Data for constructing the rating curve were available for only five events at the outlet location. This can create additional uncertainty in the results generated by the modelling work. Nevertheless, the modelling approach used here can provide critical information to understand the complexity of flooding risk, which can be further improved and updated as data collection continues. This approach still yields higher-quality results than an isolated modelling approach for each hydrodynamic phenomenon separately, an approach that has been generally adopted in the past and is still in practice.

6. Conclusions

This study addressed the critical problem of the compound flooding effect of rainfall and SLR in the coastal urban Saltwater Creek catchment in tropical northern Australia. The primary objective was to understand the flooding problem in the Saltwater Creek catchment under both current and future climate change scenarios. The scenario-based MIKE+ hydrodynamic model simulation indicated that this catchment is experiencing compound flooding, which can further inundate an area ranging from 5% to 25% under the RCP 8.5 in 2090. Another significant result obtained from this study was a variation in maximum velocity during the flooding period, ranging from 0.3 to 4 m/s. The results indicate that this catchment experiences two distinct flooding problems, with inundation in the low-lying areas and extreme velocity at the upstream locations. The current findings suggest that existing flood mitigation measures are inadequate to address the flooding challenges, which are projected to increase under climate change. However, the limitations of this study include the use of a comparatively short six-year record of rainfall, water levels, and tidal levels. In addition, some drainage data, such as the invert level of the pipe inlets and tailwater levels at outlet locations, were not available and so were interpolated using the nearest known values. In addition, under the climate change scenarios, land use change was kept constant, to understand the climate change impact only. However, flooding in the future could be worse than presented here; hence, a careful interpretation of the results should acknowledge the study's limitations. In conclusion, a compound flooding problem in this catchment is evident and is projected to worsen in the future. This necessitates a strategic response, through the integration of novel and robust economic techniques such as WSUD, to mitigate future flooding challenges.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviations	Meanings
SLR	Sea Level Rise
WSUD	Water-Sensitive Urban Design
AEP	Annual Exceedance Probability
1D	One-Dimensional
2D	Two-Dimensional
PF	Peak Flow
TRV	Total Runoff Volume
IPCC	Intergovernmental Panel on Climate Change
AHD	Australian Height Datum
CRC	Cairns Regional Council
BOM	Australian Bureau of Meteorology
DEM	Digital Elevation Model
IDW	Inverse Distance Weighting
ARR	Australian Rainfall and Runoff
ATP	Areal Temporal Pattern
ARF	Areal Reduction Factor
IFD	Intensity–Frequency–Duration
RORB	Runoff Routing
DHI	Danish Hydraulic Institute
CS	Collection System
GIS	Geographic Information System
QGIS	Quantum Geographic Information System
NSE	Nash–Sutcliffe Efficiency
RMSE	Root Mean Square Error
PBIAS	Percentage Bias
RSR	Ratio of the Root Mean Square Error to the Standard Deviation
EIA	Effective Impervious Area
FEA	Flood Extent Area
CA	Catchment Area
MWL	Maximum Water Level
IL	Initial Loss

CL	Continuous Loss
WBNM	Watershed Bounded Network Model
URBS	Unified River Basin Simulator
HEC-HMS	Hydrologic Engineering Centre Hydrologic Modelling System
XP-RAFTS	XP Rainfall Runoff Analysis Forecasting Tool for Stormwater
RCPs	Representative Concentration Pathways
DCIA	Directly Connected Impervious Area
ICIA	Indirectly Connected Impervious Area
TIA	Total Impervious Area
ICCF	Interim Climate Change Factor
CC	Current Climate

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