

Article

Impact of Climate Change on Water-Sensitive Urban Design Performances in the Wet Tropical Sub-Catchment

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Abstract

Existing drainage systems have limited capacity to mitigate future climate change-induced flooding problems effectively. However, some studies have evaluated the effectiveness of integrating Water-Sensitive Urban Design (WSUD) with existing drainage systems in mitigating flooding in tropical regions. This study examined the performance of drainage systems and integrated WSUD options under current and future climate scenarios in a sub-catchment of Saltwater Creek, a tropical catchment located in Cairns, Australia. A combination of one-dimensional (1D) and two-dimensional (1D2D) runoff generation and routing models (RORB, storm injector, and MIKE+) is used for simulating runoff and inundation. Several types of WSUDs are tested alongside different climate change scenarios to assess the impact of WSUD in flood mitigation. The results indicate that the existing grey infrastructure is insufficient to address the anticipated increase in precipitation intensity and the resulting flooding caused by climate change in the Engineers Park sub-catchment. Under future climate change scenarios, moderate rainfall events contribute to a 25% increase in peak flow (95% confidence interval = [1.5%, 0.8%]) and total runoff volume (95% confidence interval = [1.05%, 6.5%]), as per the Representative Concentration Pathway 8.5 in the 2090 scenario. Integrating WSUD with existing grey infrastructure positively contributed to reducing the flooded area by 18–54% under RCP 8.5 in 2090. However, the efficiency of these combined systems is governed by several factors such as rainfall characteristics, the climate change scenario, rain barrel and porous pavement systems, and the size and physical characteristics of the study area. In the tropics, the flooding problem is estimated to increase under future climatic conditions, and the integration of WSUD with grey infrastructure can play a positive role in reducing floods and their impacts. However, careful interpretation of results is required with an additional assessment clarifying how these systems perform in large catchments and their economic viability for extensive applications.

Keywords: climate change; flood mitigation; grey infrastructure; WSUD; flooding



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1. Introduction

Floods cause widespread human and economic losses [1]. Tropical regions are under a high risk of flooding, and these regions have experienced a fourfold increase in river flooding since 2000, the highest increase relative to other areas of the globe [2]. Rivers serve as the medium that connects urban areas and large water bodies, such as the ocean, providing a location for interaction between runoff from urban areas and the sea. Small changes in precipitation patterns and river flow have a significant impact on urban flooding as well.

While flooding in the tropics is governed mostly by climate change in catchment upstream, causing extreme precipitation [3], sea level rise (SLR) also impacts urban development in low-lying areas downstream of rivers [4]. The projected rise in global temperature is expected to lead to a significant increase in atmospheric water vapour content in the tropics, resulting in alterations to the hydrological cycle, which include an intensification of rainfall [5]. A statistically significant correlation has been found between global warming and the intensification of extreme precipitation [4]. The historical observational data since the 1950s have shown a rise in frequency and intensity of extreme rainfall events across land areas (high confidence), and human-induced climate change is probably the key driver [6]. Climate estimates for the rest of the century have indicated a constant increase in daily extreme rainfall [7]. Under climate change scenarios, average rainfall will rise in the core tropics and extra-tropics while decreasing in the subtropics [8].

Local and regional variations in precipitation characteristics depend on the variability of atmospheric circulation. Some observed shifts in atmospheric circulation are correlated with climate change. A change in storm trajectories renders certain regions wetter while others, often nearby, become drier, resulting in complex patterns of change [7]. Large-scale patterns of precipitation change linked to El Niño-Southern Oscillation (ENSO) also govern global variation [9]. The locations and timing of floods and droughts are most significantly influenced by the cycle of El Niño events, specifically in the tropics and throughout the mid-latitudes of the Pacific region [10]. The rise in local urban temperatures has also contributed to the global rise in temperature [11]. This phenomenon has increased the probability of extreme rainfall across cities, in some cases by as much as 25% [12].

Predicting urban flooding solely due to climate change has significant uncertainties, since it is a complex process, resulting from a combination of climate-related variables and local controls such as insufficient drainage, rapid urbanisation, and poor infrastructure, which further exacerbate flooding [13]. Grey measures deployed in urban areas intercept, divert, and transport runoff away from developed areas, but they often fail to perform effectively during extreme rainfall events due to insufficient capacity [14]. Some studies have raised questions about the robustness of grey measures to perform under a range of flooding scenarios and have discussed other flexible and robust systems [15,16].

Water-Sensitive Urban Design (WSUD) is an alternative method for attenuating surface/peak runoff, providing flood mitigation [16–18]. In Australia, the National Water Commission (2004, p. 30) [19] defined WSUD as “the integration of urban planning with the management, protection and conservation of the urban water cycle that ensures urban water management is sensitive to natural hydrological and ecological processes”. WSUD has been integrated with grey measures to manage stormwater and flood mitigation [20]. Previous studies in the tropics have shown that WSUD’s surface runoff reduction capacity ranges from 3.6% to 78% and peak flow reduction from 22.8% to 67.8% [21]. The reported WSUD performance in mitigating runoff reduction in the sub-tropic climate ranges from 58% to 60% [22]. Furthermore, the flood reduction performance of WSUD in semi-arid climatic regions varies across different locations and land use areas, including buildings, sidewalks, and open spaces, with a range of 14% to 55% [23].

The studies in tropical catchments that support this approach are limited in number compared to other climatic zones [24–29]. In addition, the existing methods of WSUD practiced in the tropics are based on guidelines developed based on results from temperate or arid climatic zones [30–33]. While these documents do not accurately represent the climatic or topographical features of the tropics, the design and practices of WSUD, as measured and developed in relation to these documents, are potentially dysfunctional. Thus, these critical knowledge gaps in the tropics have impacted the extensive implementation of WSUD. There is a continuous need for research into the practical application of WSUD systems and their efficiency in reducing flooding in the tropics, including the impacts of a changing climate.

Therefore, to bridge the research gap, this study focuses on understanding the integration of WSUD with grey measures for reducing localised flooding induced by climate change in a tropical catchment. To understand these issues, the following research questions were posed: (i) What is the likely impact of climate change on localised flooding? (ii) Can WSUD measures contribute to flood mitigation after integration with existing grey infrastructure under climate change? (iii) What factors affect WSUD application in the tropics under climate change?

2. Materials and Methods

2.1. Study Site

The selected study site is Engineers Park, a small sub-catchment of the Saltwater Creek catchment in Cairns city, Queensland, Australia (Latitude = -16.911 , Longitude = 145.72) (Figure 1). This site was previously used for the hydrodynamic study of floods in [34] and was also utilised in this study to expand the research scope to include climate change. This catchment has a total area of 0.27 km^2 , a small fraction of the Saltwater Creek catchment, which spans a total area of 16 km^2 . The catchment is topographically characterised by a short width of approximately 600 m and a significant elevation difference, ranging from about 11 m Australian Height Datum (AHD) at the outlet to 139 m AHD at the top.

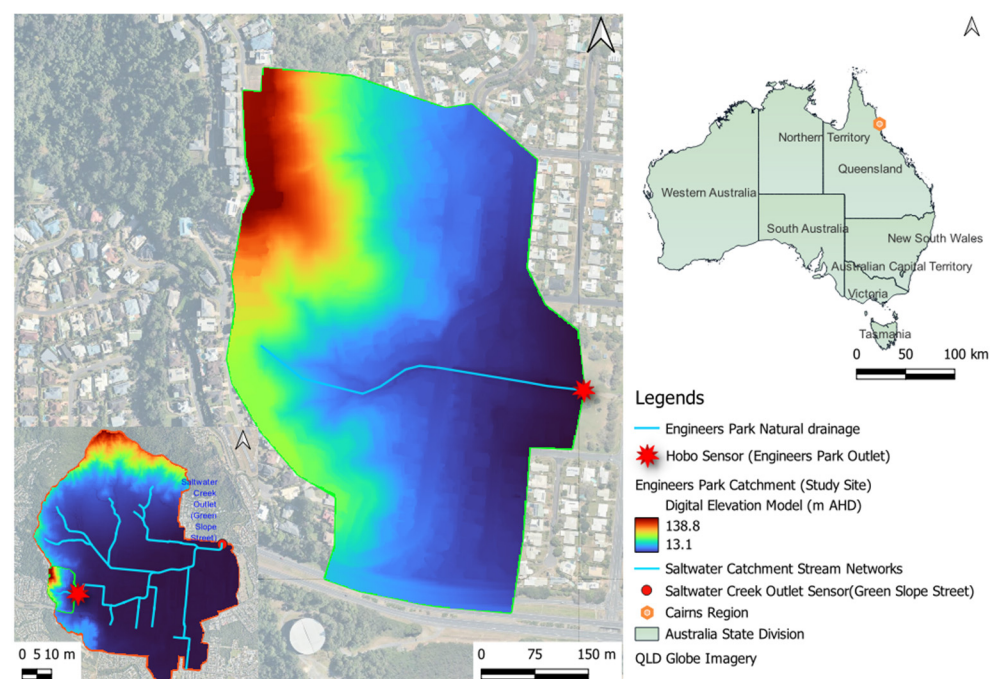


Figure 1. Boundary of Engineers Park in the Saltwater Creek catchment in Cairns City, and digital elevation model for Engineers Park, Cairns Regional Council (CRC), Queensland, Australia, with key features highlighted.

Engineers Park is the uppermost sub-catchment of Saltwater Creek, located on the western side of the Whitfield range. This study site is a perfect example for evaluating the performance of existing grey measures and the impact of WSUD measures. The assessment of WSUD in such a topography can yield several significant findings, including the impact of slope on flooding and the application of WSUD, as well as the spatial prioritisation of these measures. Comprehensive flood modelling was undertaken at a small spatial scale, focusing on understanding rainfall-driven localised flooding at this study site, before the simulation work was expanded to the entire catchment. Generally, upstream and mid-catchment areas have a significant influence on the amount of runoff attributed to the drainage network and substantially affect the overall catchment flooding [35]. Additionally, while the study area is a steep catchment, the catchment slope has less significance in inducing flood generation during small-sized rainfall events. The flooding problem is influenced by localised changes within the catchments, such as the underperformance of grey measures. Therefore, the intervention of WSUD measures within the catchment can be evaluated, which can significantly reduce the runoff transported to the grey measures and can have a positive impact on reducing the flood hazard.

The Australian Bureau of Meteorology (BOM) notes that Cairns falls in the wet tropical climatic zone. 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 data period from 1943 to 2024, was analysed. The maximum monthly precipitation received during the wet season, from December to April, can reach 1417 mm. In contrast, in the dry season, from July to November, precipitation is lowest. The area has an annual average rainfall ranging between 1997 mm and 3148 mm, with a long-term average yearly rainfall of 2028 mm. In addition, 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

All datasets used in this modelling study are explained and discussed in detail in earlier literature published by similar authors [34]. Since this work is an extension of earlier work published by a similar group of authors for the same study site, to avoid redundancy and repetition of work, this study has only listed the data and sources in Table 1.

Table 1. Data types and sources adopted during the flood modelling study [36–43].

Data	Sources	Open/Purchase	Resolution
Rainfall data	CRC		Tipping bucket rain gauge
Digital elevation model (DEM)	CRC	-	High resolution (0.5×0.5 , 2021)
Shapefile (land use/land cover)	CRC	-	
Drainage network (pipe, manhole, inlets details)	CRC	-	
Hydrological input (Areal Reduction Factors (ARFs), Areal Temporal Pattern (ATP), Intensity–Duration–Frequency (IDF))	[37,43]	Open source	
Soil type	[36]	Open source	

Table 1. *Cont.*

Data	Sources	Open/Purchase	Resolution
Water level data	[39]	Fieldwork	Hobo Pressure transducer (short duration)
Climate data	[38]	Open source	High resolution
RORB model	[40]	Open source	
Storm injector	[41]	Purchase	
MIKE+	[42]	Open source (Student Version-Unlimited)	

A high-resolution 0.5 m × 0.5 m digital elevation model (DEM), derived from a 2021 LiDAR survey provided by the Cairns Regional Council (CRC), was used to define catchment topography, delineate the catchment, and support hydrological and hydraulic modelling. Geological and soil data, including the Hodgkinson formation, were sourced from the Geological Survey of Queensland. The CRC also supplied the drainage network and daily rainfall data, which were collected via a tipping-bucket rain gauge. Water level measurements were recorded at 5 min intervals using a pressure transducer sensor between February and September 2023, with corresponding velocity measurements taken five times during the wet season to establish a rating curve for discharge estimation. The catchment features a diverse range of land uses, with approximately 50% of the area covered by green spaces and tropical rainforest, transitioning from forested areas upstream to urban development downstream.

2.3. Method

2.3.1. Modelling Approach and Tools

The research approach adopted during the preliminary phase of data collection, the modelling tools used, model setup, calibration and validation, simulation scenarios, and the outcomes of the work are discussed in detail. The flow chart presented in Figure 2 shows the process flow connection adopted for this research work.

The tools adopted during this study have been explained in detail in an earlier study [34], and to avoid repetition and redundancy, this study has only listed the tools in Table 1. This study has adopted a combination of open-source and commercial hydrological and hydraulic modelling tools. The open-source, runoff-routing, lumped conceptual RORB version 6.45 model was adopted for hydrological assessment [40]. This tool is a streamflow routing program that computes hydrographs from precipitation, deducting losses from precipitation to generate runoff [44]. In addition, the commercial software Storm Injector 1.4.0_HL is an integrated platform where catchment files are developed using hydrological models, such as RORB [41]. Furthermore, this study adopted the MIKE+ commercial modelling tool over other modelling tools, developed by the Danish Hydraulic Institute (DHI), Denmark [42]. This research adopted the calibrated and validated MIKE+ model setup from earlier research work on Engineers Park, conducted by an identical team of authors [34]. This model was used for additional simulation scenarios, as explained in the following paragraphs.

The model calibration and validation were assessed using standard goodness-of-fit criteria. The Nash–Sutcliffe Efficiency (NSE) indicates the predictive performance of the model, where values closer to 1 reflect better agreement between observed and modelled data. The Root Mean Square Error (RMSE) measures the spread of prediction errors,

indicating how closely the model results match observed values. The Percentage Bias (PBIAS) evaluates whether the model tends to overestimate or underestimate the observed data. The equations and approach adopted to evaluate the model's performance have been detailed previously [34].

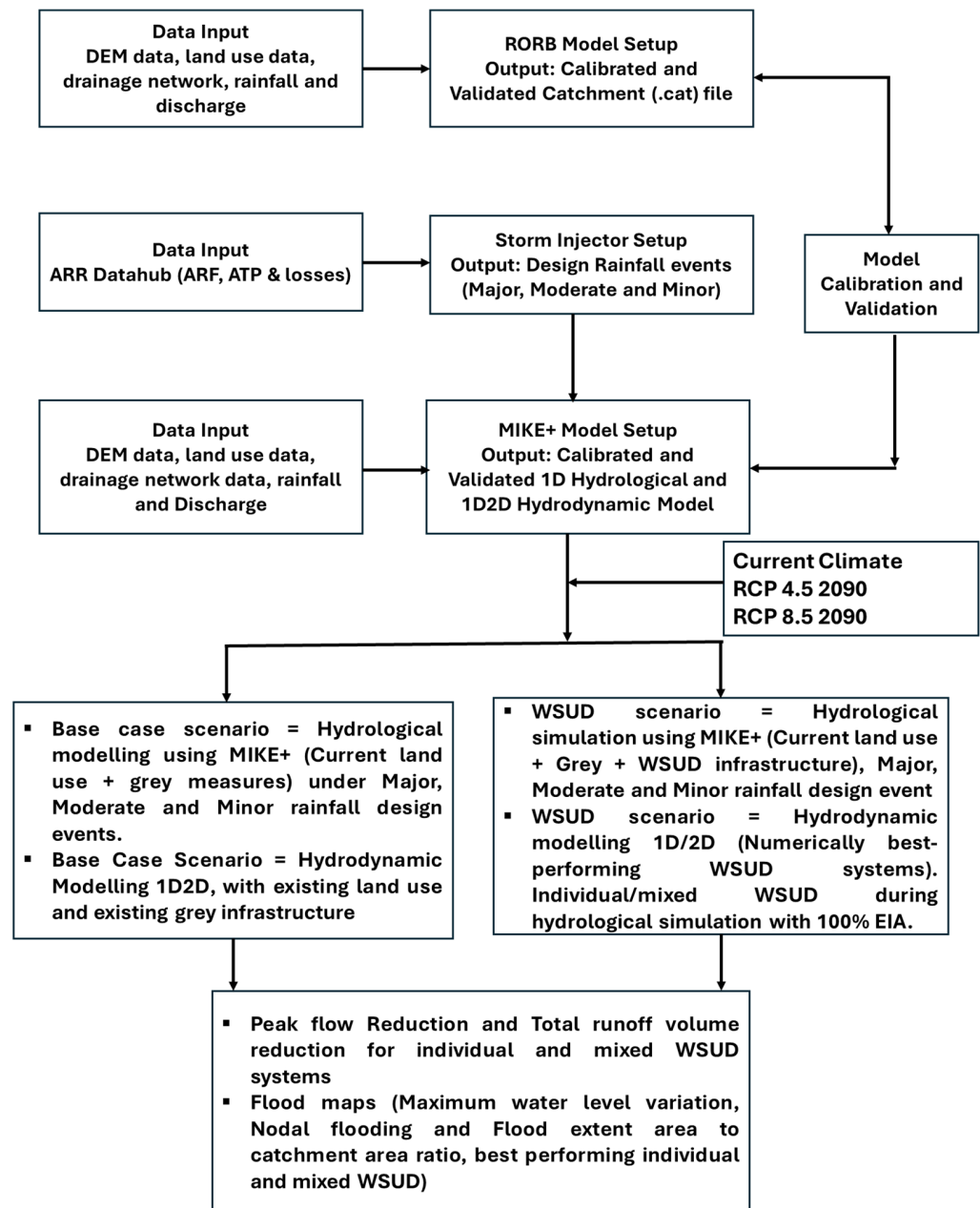


Figure 2. Flood modelling approach with flowchart steps.

2.3.2. Climate Change Scenario Calculation

The Intergovernmental Panel on Climate Change (IPCC) has provided representative concentration pathway (RCP) scenarios used to model and project future greenhouse gas emission rates and their concentration in the atmosphere, resulting in climate change [45]. The method used to incorporate climate change scenarios in rainfall design events was detailed in the Australian Rainfall Runoff (ARR) 2019 [46]. This method facilitates the incorporation of temperature data into rainfall intensity or depth for future scenarios. As a scaling factor, the direct conversion of rainfall data from intensity, frequency, and duration (IFD) is the least accurate and has high uncertainty in rainfall measurements. Therefore,

temperature data are often used as a parameter to assist in developing a scaling factor, as follows:

$$\text{Rainfall intensity/depth scaling factor (Ip)} = I_{\text{ARR}} \times 1.05^{T_m} \quad (1)$$

where I_{ARR} refers to the design rainfall intensity obtained from the IDF curve, 1.05 = presumed temperature scaling factor based on the exponential relationship between temperature and humidity, ARR = Australian rainfall runoff, and T_m = temperature at the midpoint or median of the selected class interval. The temperature data were adopted due to higher confidence in the simulation results for temperature relative to rainfall. ARR is suggested using an adjustment factor for IFD, as advised by the temperature projection in [46].

This research used the Storm Injector to create climate scenarios. The catchment file prepared using the RORB model was imported into the Storm Injector, including storm files from the ARR data hub [37], and the intensity–frequency–duration curve from the BOM [43] can also be injected. This tool was used to incorporate climate change scenarios and calculate rainfall design events under future climate scenarios. Climate change open data was obtained from the Queensland Long Paddock [38]. This platform provides a regionalised summary of statistical data for Queensland, featuring a high spatial resolution.

2.3.3. WSUD Planning and Deployment

WSUD deployment in MIKE+ can be conducted by defining its characteristics, coverage, and numbers. The SWMM low-impact development (LID) toolbox, coupled with this platform, was used to define the WSUD properties (detailed in Appendix A, Tables A1 and A2) and deployment in the catchment, as well as the hydraulic connections to the existing drainage network [47]. To deploy WSUD measures, the whole catchment of the study site was divided into several sub-catchments, as shown in Figure 3. Primarily, this approach utilises the effective impervious area (EIA) as the basis for defining the area coverage of the WSUD system, explicitly referring to the “collecting area.” The MIKE+ automation LID Deployment tool calculates the directly connected impervious area (DCIA) using the total impervious area of each sub-catchment. The area assessed for WSUD implementation within the study site is quantified and shown in Table 2.



Figure 3. The sub-catchment division of the Engineers Park Catchment has been adopted for the implementation of WSUD.

Table 2. WSUD application distribution and coverage.

WSUD	Collecting Area (m ²)	Area Distributions (m ²)					
		10% EIA	20% EIA	40% EIA	60% EIA	80% EIA	100% EIA
Rain Barrel (RB)	12,330	3–27	7–53	13–107	20–160	27–213	33–267
Porous Pavement (PP)—m ²	12,110	1–25	3–50	5–100	8–150	10–150	13–250
Bio-retention (BR)—m ²	12,700	3–27	7–53	13–107	20–160	27–213	33–267
Rain Garden (RG)—m ²	12,700	3–27	7–53	13–107	20–160	27–213	33–267
Infiltration Trench (VS)—m ²	12,700	3–27	7–53	13–107	20–160	27–213	33–267

2.3.4. Modelling Simulation Scenarios

The modelling under the current and climate change scenarios adopted for this study is presented in Table 3. The RCP, a greenhouse gas concentration emission projection considered by the IPCC for modelling the future climate state, is adopted for modelling purposes. The three climate scenarios considered in this study are the current climate (CC), RCP 4.5, and RCP 8.5 scenarios. RCP 4.5 was considered for the assessment, representing a moderate emission trajectory and stabilisation scenario. However, stable climate change impacts, such as changes in temperature patterns, rainfall, and sea level rise, are projected to be observed during this scenario [5]. Furthermore, RCP 8.5 is considered a high-emission pathway based on whether limited or no mitigation measures were implemented to reduce GHG emissions.

Table 3. Model simulation scenarios.

Scenarios	Descriptions
Current Climate (CC) Scenarios	• MIKE+ hydrological (kinematic wave) simulation using existing land-use data, existing grey infrastructure (base case scenario). • MIKE+ hydrological simulation of various WSUD systems with 10%, 20%, 40%, 60%, 80%, and 100% effective impervious area (EIA) reduction. • Individual WSUDs: Porous Pavement (PP), Rain Barrel (RB), Bio-retention (BR), Rain Garden (RG), Infiltration Trench (IT). • Mixed systems PP+RB (M1), PP+RB+BR (M2), PP+RB+BR+RG (M3), and PP+RB+BR+RG+IT (M4).
	• Hydrodynamic modelling, 1-dimensional (1D) and 2- dimensional (2D), coupled with 1D2D (numerically best-performing WSUD systems). • Individual/mixed WSUDs during hydrological simulation with 100% EIA.
RCP 4.5 in 2090 Scenarios	• MIKE+ hydrological (kinematic wave) simulation using existing land-use data, existing grey infrastructure (base case scenario). • MIKE+ hydrological simulation of various WSUD systems with 10%, 20%, 40%, 60%, 80%, and 100% EIA reduction. • The individual WSUDs adopted for simulation are PP, RB, BR, RG, and IT. • Mixed WSUDs adopted for simulation are M1, M2, M3, and M4.
	• Hydrodynamic modelling 1D2D (numerically best-performing WSUD systems). • Individual/mixed WSUD during hydrological simulation with 100% EIA.

Table 3. Cont.

Scenarios	Descriptions
RCP 8.5 in 2090 Scenarios	• MIKE+ hydrological (kinematic wave) simulation using existing land-use data, existing grey infrastructure (base case scenario). • MIKE+ hydrological simulation of various WSUD systems with 10%, 20%, 40%, 60%, 80%, and 100% EIA reduction. • The individual WSUDs adopted for simulation are PP, BR, BR, RG, and IT. • MIKE+ hydrological simulation of mixed WSUDs adopted for simulation are M1, M2, M3, and M4.
	• Hydrodynamic modelling 1D2D (numerically best-performing WSUD systems). • Individual/mixed WSUD during hydrological simulation with 100% EIA.

This study incorporated several WSUD features aimed at improving stormwater management and enhancing urban resilience. These included bio-retention systems and rain gardens, which use vegetation and engineered soils to filter and slow runoff; rain barrels, which capture and store rainwater for reuse; infiltration trenches, designed to promote groundwater recharge by allowing runoff to soak into the ground; and porous pavements, which reduce surface runoff by enabling water to pass through the pavement surface. Collectively, these WSUD measures help reduce flood risk, improve water quality, and support sustainable urban water management. For more details on the characteristics of these systems, refer to Appendix A.

3. Results

3.1. Climate Change Impact on Design Rainfall Characteristics

The alteration in rainfall depth under climate change scenarios is estimated (Table 4). The comparative assessment of rainfall depth revealed a consistent rise during the RCP 4.5 and RCP 8.5 scenarios for 2090 across minor, moderate, and major events. For instance, rainfall depth increased by approximately 7.5% and 14% during major events under RCP 4.5 in 2090 and RCP 8.5 in 2090, respectively, relative to the CC. Similarly, minor and moderate rainfall design events followed a similar pattern of change. The IPCC report highlighted the rainfall correlation with the Clausius–Clapeyron relationship, indicating a 7% rise in rainfall per 1 °C increase in temperature [5]. However, this study observed a marginally higher rainfall increment than the IPCC report. This was because the 7% increase in rainfall for every degree is an average value that varies depending on the local climate and data [48]. The application of high-resolution local climatic data from Queensland’s Long Paddock [38] contributed to providing marginally different results from the IPCC report.

Table 4. Design event rainfall depth and critical time of peak flow generation under different climate scenarios.

AEP/Critical Time	Current Climate (CC) (mm)	RCP 4.5 2090 (mm)	RCP 8.5 in 2090 (mm)
Minor (63.2% AEP), Critical time: 30 min	34	36	39
Moderate (20% AEP), Critical time: 30 min	47	51	55
Major (1% AEP), Critical time: 25 min	66	70	75

The critical time to peak flow was 30 min for minor and moderate events, and 25 min for major events. Despite the increase in rainfall depth under future climate scenarios, the critical time for peak flow generation for this catchment remains constant for all scenarios. The critical time consistency might be due to the lumped nature of the RORB model. On the other hand, catchment rainfall runoff dynamics are governed by several different parameters, such as topography, land use features [49], antecedent moisture [50], and hydraulic structures [51]. This finding suggests that an in-depth understanding of local catchment characteristics is key to assessing the impact of climate change.

3.2. Flood Mitigation Under Climate Change Scenarios

A comprehensive evaluation of WSUD performance under current and future climate change scenarios, considering both 1D and coupled 1D2D results (flood maps included in Appendix A, Figures A1 and A2), is presented to reveal the effectiveness of individual and mixed WSUD technologies.

3.2.1. Grey Infrastructural Performance Under Climate Change

During this simulation, rainfall intensity was the only dynamic parameter that influenced the flow in the catchment. Other parameters affecting flow, such as land use, were kept constant to ensure comparable results. An increasing trend in peak flow and total runoff volume was observed with existing grey infrastructure under climate change scenarios across all rainfall scenarios (Table 5). The comparative assessment of peak flow during the CC and RCP 8.5 in 2090 revealed increments of 20%, 25%, and 16% (95% confidence interval for the mean error [−1.5%, 0.8%]) during major, moderate, and minor AEP, respectively. The total runoff volume also exhibited increments of 20%, 25%, and 19% (95% confidence interval for the mean error [−1.05%, 6.5%]) when compared between CC and RCP 8.5 in 2090 under major, moderate, and minor events, respectively. These moderate-sized rainfall events exhibited the highest peak flow and total runoff volume increments, followed by major and minor events under climate scenarios, indicating that moderate-sized rainfall events can also exacerbate flooding to a similar extent as major events. The spatially distributed grey infrastructure within the study site plays a critical role in governing this phenomenon. Runoff generated from different catchment locations was efficiently intercepted and transported, particularly during moderate events. Subsequently, natural water loss mechanisms, such as infiltration and retention, were reduced during the runoff travel time, resulting in higher peak flow and total runoff volume values during such events. These findings highlight the critical role of grey measures in exacerbating flooding conditions in future climate scenarios.

Table 5. Peak flow and total runoff volume alteration under different climate scenarios.

Peak flow (m ³ /s)			
AEP	CC	RCP 4.5 in 2090	RCP 8.5 in 2090
Minor	4	4	5
Moderate	6	7	8
Major	10	11	12
Total runoff volume (m ³)			
Minor	0.33×10^6	0.38×10^6	0.41×10^6
Moderate	0.47×10^6	0.58×10^6	0.63×10^6
Major	1.56×10^6	1.75×10^6	1.95×10^6

3.2.2. Individual WSUD Performance

The peak flow and total runoff volume reduction achieved by individual WSUD systems under different climate scenarios are presented in Figures 4 and 5 (average results in

Appendix A, Table A3). Rain barrel was the best-performing WSUD system, demonstrating peak flow and total runoff volume reductions ranging from 1% to 42% and 7% to 46%, respectively. On the other hand, bio-retention was the worst-performing system, with peak flow and total runoff volume reductions ranging from −6.0% to 40% and 1% to 42%, respectively. Overall, the individual WSUD systems' peak flow and total runoff volume reductions follow an ascending order of bio-retention < rain garden < infiltration trench < porous pavement < rain barrel.

A comparative analysis of the best- and worst-performing WSUD efficiencies under rainfall events reveals that the percentage reduction in peak flow ranges from 1% to 21% under climate change (CC) and from 6% to 27% for the RCP 8.5 in 2090. At the same time, the efficiency difference between the best and worst WSUDs under climate change scenarios ranges from 1% to 7% and 0% to 4% during major rainfall events under CC and RCP 8.5 in 2090, respectively. Similarly, total runoff volume reduction performance shows a small degree of variation. During minor rainfall, total runoff volume reduction ranges from 11% to 15% and 2% to 18% for rain barrel and bio-retention, respectively, for RCP 8.5 in 2090. On the other hand, under RCP 8.5 in 2090, total runoff volume reduction differences between rain barrels and bio-retention range from 1.5% to 3.9% during major rainfall, with bio-retention intermittently showing a negative performance (−2.6%). The sensitivity of individual WSUD peak flow reduction efficiency is notably high compared to total runoff volume, remarkably during rainfall events.

The wide range of WSUD performance variation under rainfall design events was due to significant alteration in rainfall depth, i.e., by 29% and 48% during major rainfall relative to minor rainfall events. However, the rainfall depth variation compared to the climate scenario between CC and RCP 8.5 in 2090 was only about 14%. The rainfall variation between minor and major design events under the current climate was almost 2 to 3 times higher than in the climate scenarios. The performance of WSUD systems showed a nominal decline in efficiency of flood mitigation when comparing current and future climate scenarios. The selection of the rainfall design event is a critical factor, followed by climate change factors, in determining the performance of WSUD flood mitigation [52].

The minimum effective impervious area reduction required to achieve a positive peak flow reduction under CC was a 10% reduction in effective impervious area during minor rainfall. Under CC, an effective impervious area reduction of 10% or less after intervention by WSUD resulted in a negative peak flow reduction, implying an increase in peak flow. In addition, under RCP 8.5 in 2090, an effective impervious area reduction of <20% yielded a negative result. In comparison, for RCP 8.5 in 2090, WSUD, such as bio-retention and RG, resulted in higher negative results than the CC scenario. The study also found that the increasingly negative values become more noticeable during peak flow reduction, resulting from the lower WSUD coverage of a 20% effective impervious area, particularly during moderate or minor rainfall events, in addition to major events.

In contrast, with the maximum effective impervious area reduction, the peak flow efficiency remains almost constant after a 60% effective impervious area under current climate conditions. However, the WSUD peak flow reduction, particularly effective impervious area reduction under RCP 8.5 in 2090, requires an 80% effective impervious area reduction to achieve maximum efficiency. The results suggest that the impact of climate change necessitates an increase in effective impervious area reduction in proportion to the effect during minor, moderate, and major events. However, a 40% to 60% effective impervious area reduction with WSUD application appears to be the optimal peak flow reduction for all WSUD types under current and future climate change scenarios.

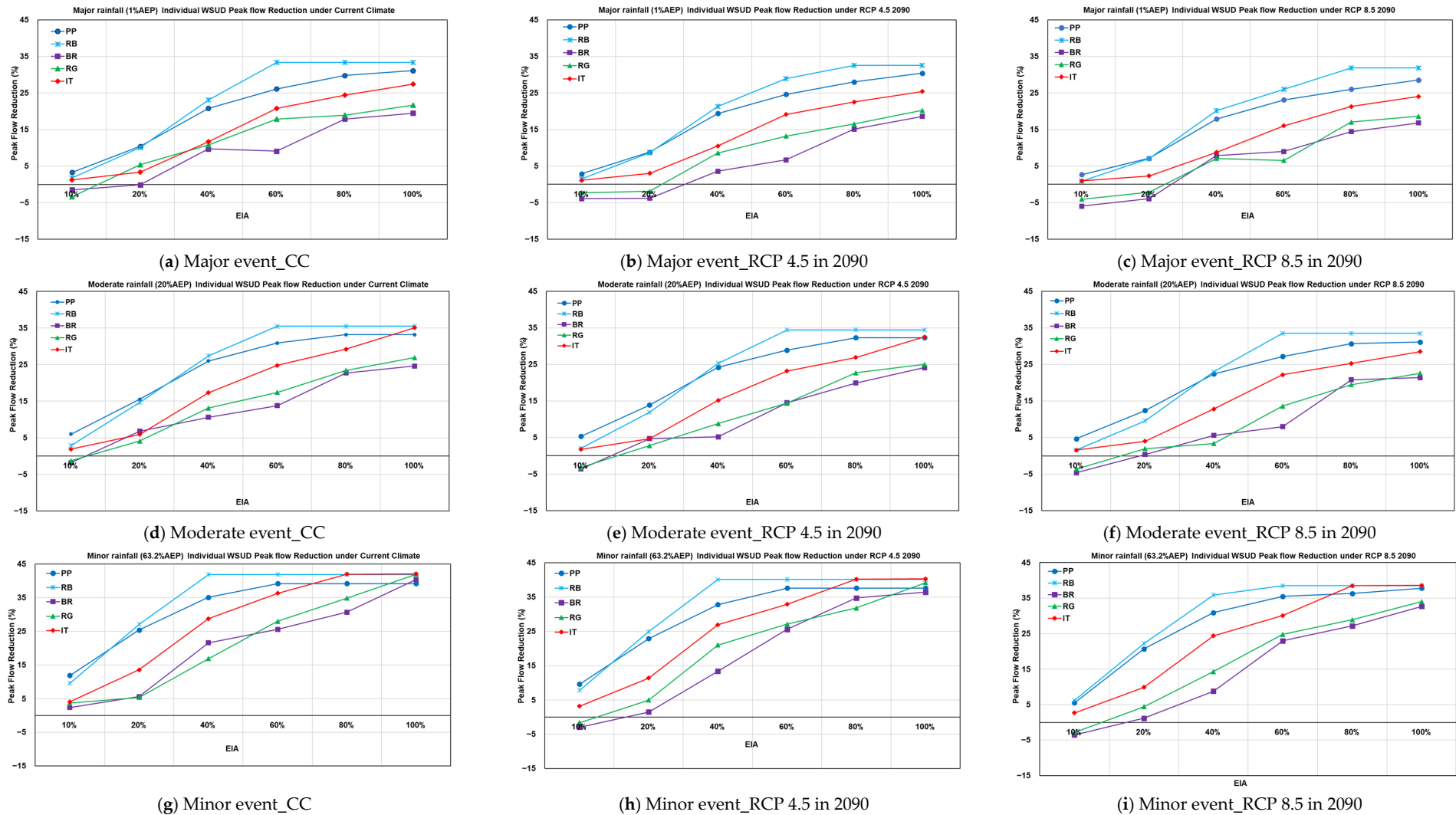


Figure 4. Peak flow reduction with individual WSUD performance under (a) Major event_CC, (b) Major event_RCP 4.5 in 2090, (c) Major_RCP 8.5 in 2090, (d) Moderate_CC, (e) Moderate_RCP 4.5 in 2090, (f) Moderate_RCP 8.5 in 2090, (g) Minor_CC, (h) Minor_RCP 4.5 in 2090, and (i) Minor_RCP 8.5 in 2090.

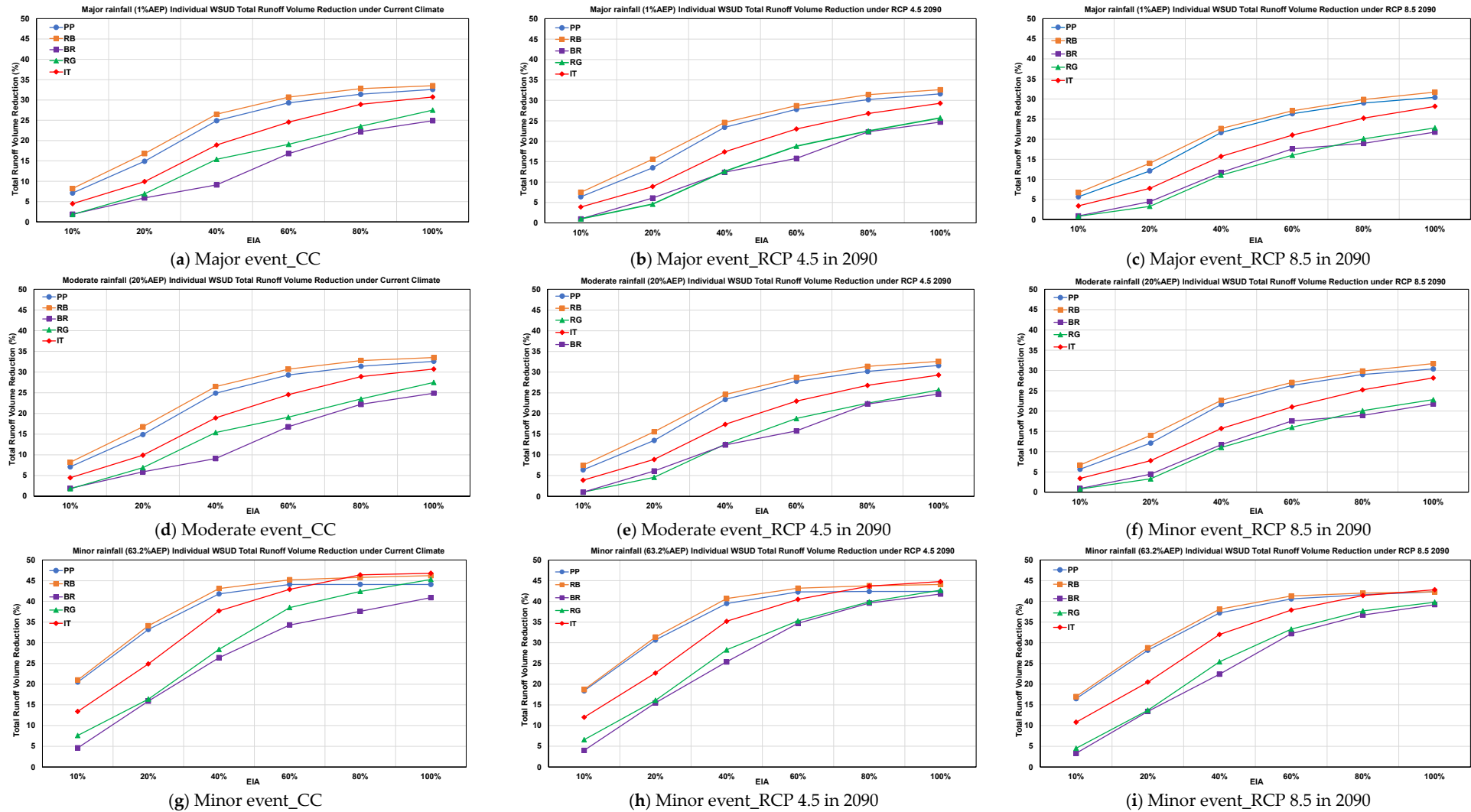


Figure 5. Total runoff volume reduction with individual WSUD performance under (a) Major event_CC, (b) Major event_RCP 4.5 in 2090, (c) Major event_RCP 8.5 in 2090, (d) Moderate_CC, (e) Moderate_RCP 4.5 in 2090, (f) Moderate_RCP 8.5 in 2090, (g) Minor_CC, (h) Minor_RCP 4.5 in 2090, and (i) Minor_RCP 8.5 in 2090.

Examining the trend of peak flow and total runoff volume reduction efficiency, the WSUD peak flow reduction exhibits a non-linear relationship with the decrease in effective impervious area, influenced by the climate change impact on rainfall events. Climate change scenarios are projected to increase rainfall intensity, implying an increase in complexity and potential uncertainty in their performance. The relationship of WSUD performance was governed by effective impervious area reduction versus peak flow and total runoff volume reduction, exhibiting a linear trend until a 60% effective impervious area under CC, after which the results remain constant even with an effective impervious area increment to a 100% effective impervious area. However, under RCP 8.5 in 2090 climate change scenarios, WSUD showed a linear relationship with efficiency until an 80% reduction in impervious area was achieved, after which it remained constant or exhibited a nominal increment towards a 100% effective impervious area.

With an increase in rainfall extremeness, driven by climate change, a large area of the total catchment needs to be managed by the WSUD system to achieve a positive contribution to reducing the flooding condition. However, it is not always possible to reduce the entire effective impervious area due to economic and technical limitations. Therefore, to achieve the optimal positive results of flood reduction, in general, the relationship between WSUD efficiency and effective impervious area reduction exhibited a varying non-linear trend, depending on the rainfall design events; this trend becomes more pronounced with the impact of climate change, raising further concerns about WSUD performance under future climate change scenarios.

3.2.3. Mixed WSUD Performance

The application of a mixed WSUD approach assumes that different individual methods can be combined to enhance the flood mitigation capacity. The mixed WSUD peak flow and total runoff volume reduction is presented in Figures 6 and 7. The graphs indicate that M1 (which is porous pavement + rain barrel) and M4 (which is porous pavement + rain barrel + bio-retention + rain garden + infiltration trench) are the most and least effective mixed WSUDs for peak flow and total runoff volume reduction, respectively. Mixed WSUDs can be ranked in ascending order: $M1 > M2 > M3 > M4$, for all rainfall and climate scenarios. The individual performance of WSUD in this catchment controlled the overall ranking of the WSUD options.

Earlier studies have reported that combining different WSUDs helps improve peak flow reduction [18,21,53–55]. The combination of individual systems influences the functions of both retention and infiltration-based systems, thereby enhancing overall efficiency. The low infiltration capacity of the soil in this catchment limited the effectiveness of the infiltration-based systems, and the combination of retention and infiltration-based systems contributed to reducing the negative results with small effective impervious area reductions.

Furthermore, combining different WSUD systems significantly reduced the inconsistency in results compared to those of individual WSUD systems under climate change scenarios. The negative peak flow value, with the minimum effective impervious area reduction, observed positive results or improvements in efficiency. For illustration, the discrepancy in peak flow between the best- and worst-performing WSUDs during major rainfall under RCP 8.5 in 2090 is 15%, with a 100% effective impervious area for an individual WSUD component. It reduced the discrepancy of individual WSUD components in peak flow by 7.6%. A 50% improvement in alignment between options was observed with the combination of different WSUD systems. The inconsistency in efficiency was reduced after combining the WSUD system under a broader range of uncertain scenarios, improving the reliability of WSUD performance under uncertain conditions.

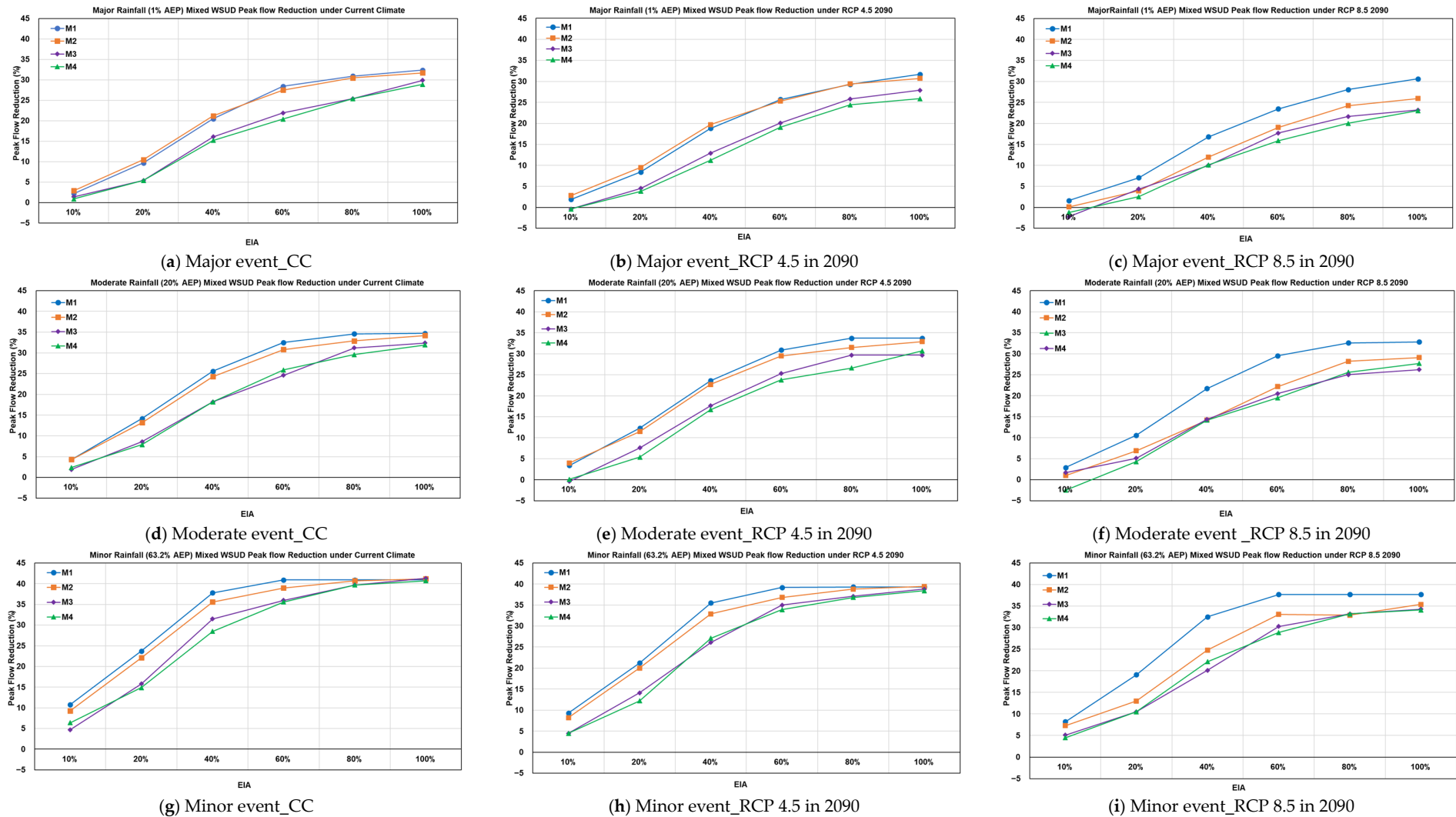


Figure 6. Peak flow reduction with mixed WSUD performance under (a) Major event_CC, (b) Major event_RCP 4.5 in 2090, (c) Major_RCP 8.5 in 2090, (d) Moderate event_CC, (e) Moderate_RCP 4.5 in 2090, (f) Moderate_RCP 8.5 in 2090, (g) Minor event_CC, (h) Minor_RCP 4.5 in 2090, and (i) Minor_RCP 8.5 in 2090.

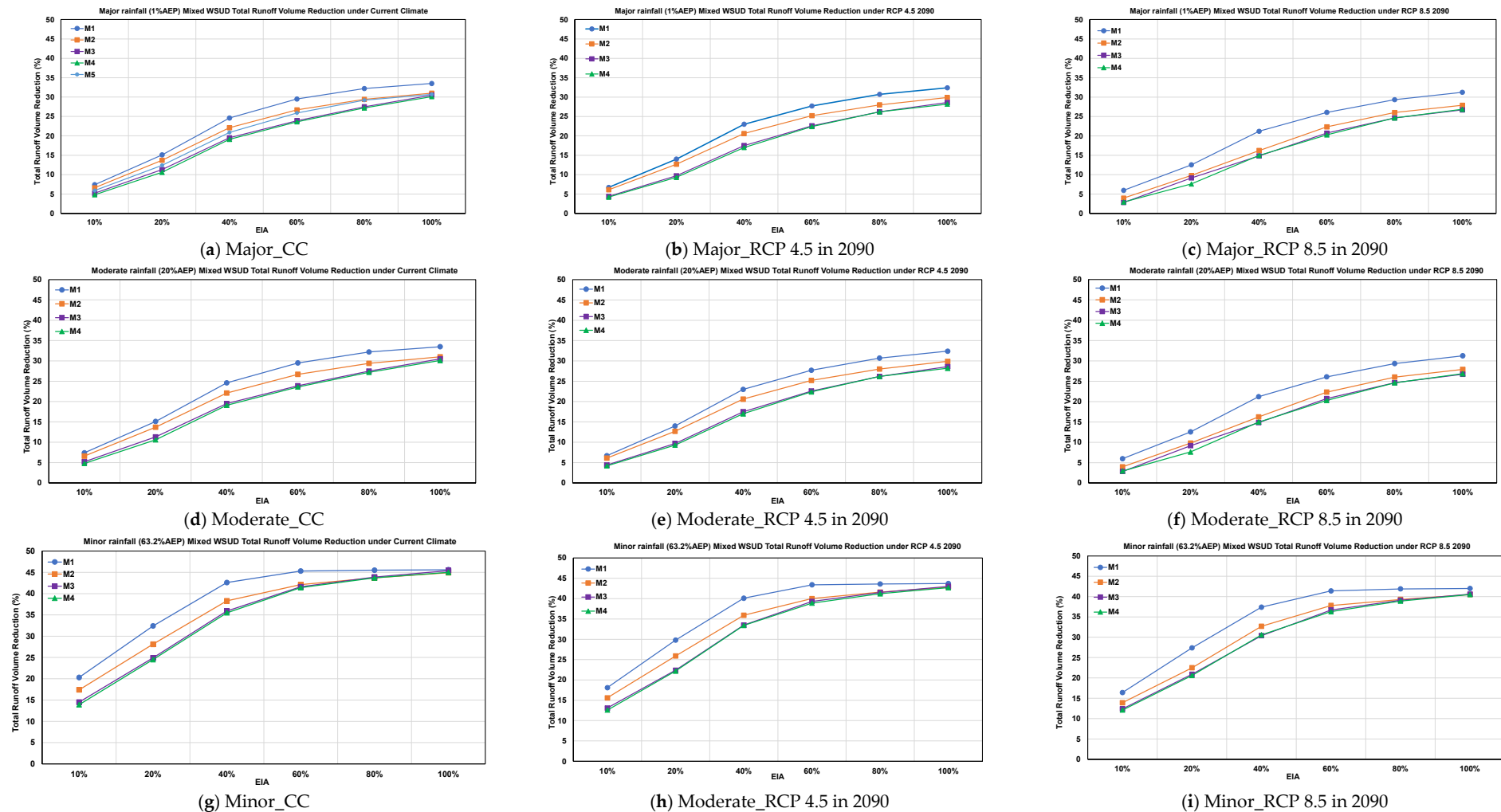


Figure 7. Total runoff volume reduction with mixed WSUD performance under (a) Major event_CC, (b) Major event_RCP 4.5 in 2090, (c) Major event_RCP 8.5 in 2090, (d) Moderate_CC, (e) Moderate_RCP 4.5 in 2090, (f) Moderate_RCP 8.5 in 2090, (g) Minor_CC, (h) Minor_RCP 4.5 in 2090, and (i) Minor_RCP 8.5 in 2090.

3.2.4. WSUD Flood Mitigations

To assess the flood mitigation performance of WSUD, a coupled 1D2D model was used to simulate both individual and combined WSUD systems (Figure 8). Results showed water level variations ranging from 0.05 m to 1.03 m across different rainfall and climate scenarios. Higher water level changes occurred in channel and roadside areas, especially near culverts and road ends, under intense rainfall. Integrating WSUD with grey infrastructure reduced maximum water levels at the catchment outlet by 7–20% under current climate conditions, and by 3–7% under RCP 8.5 for 2090. WSUD also significantly reduced overland flow, though extreme rainfall under climate change scenarios challenged inlet and pipe capacities, leading to localised overflow.

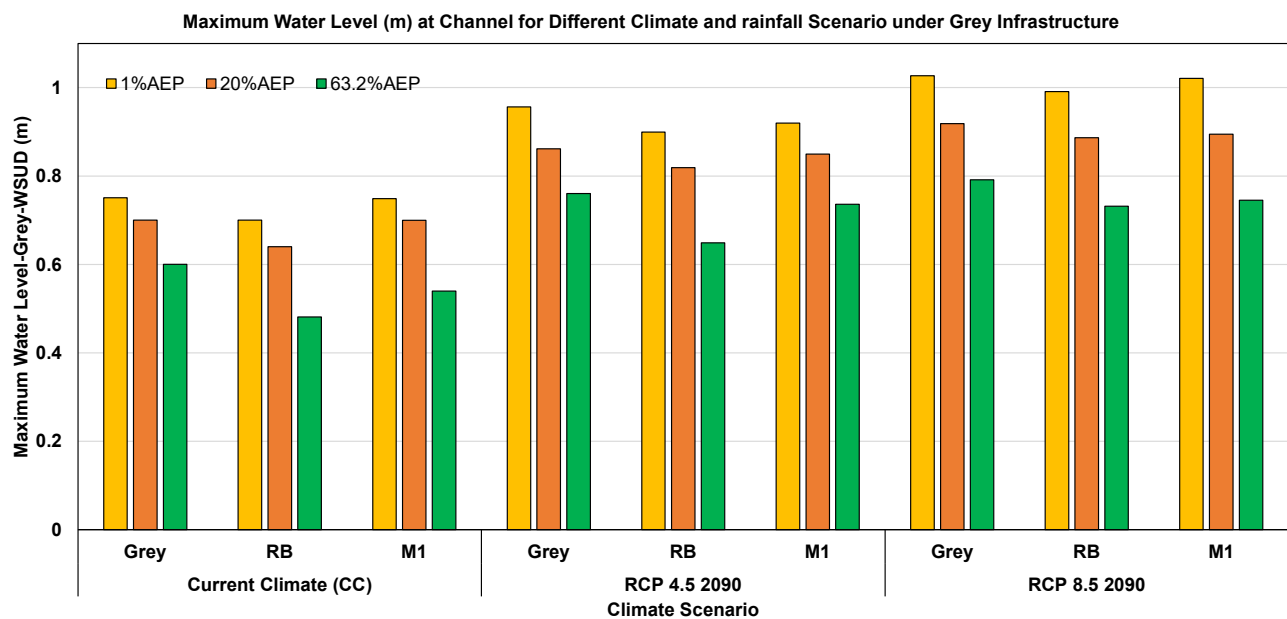


Figure 8. Engineers Park maximum water level variation under CC, RCP 4.5 in 2090, and RCP 8.5 in 2090 with grey and best WSUDs (rain barrel and M1) with 100% effective impervious area.

The maximum velocity variation at the channel outlet under different rainfall and climate scenarios ranged from 1 to 3.5 m/s under current conditions and up to 5 m/s under RCP 8.5 by 2090, indicating a potential 40% increase due to intensified rainfall (Figure 9). While velocity is less discussed in the literature compared to inundation or the water level, it is critical for assessing the flood hazard. The increase is attributed not only to greater runoff but also to the steep upper catchment and grey infrastructure. In contrast, effective WSUD measures like rain barrels and M1 significantly reduced velocities by 4–48%, particularly under major and moderate rainfall events. High velocities pose safety risks, transporting debris and increasing flood damage potential, even during minor events.

The number of flooded nodes under different climate scenarios and rainfall conditions varied notably with the integration of WSUD (Figure 10). Under RCP 8.5 in 2090, flooded nodes increased by up to 33% and 62% during moderate and minor events, respectively, due to higher rainfall and runoff. However, WSUD implementation led to a reduction in flooded nodes by up to 30% (current climate) and 57% (RCP 8.5) during moderate events, and up to 62% and 25% under minor events, respectively (Figure 10). The data suggest that WSUD is most effective in reducing node flooding during moderate and minor rainfall, while its impact is limited under major events.

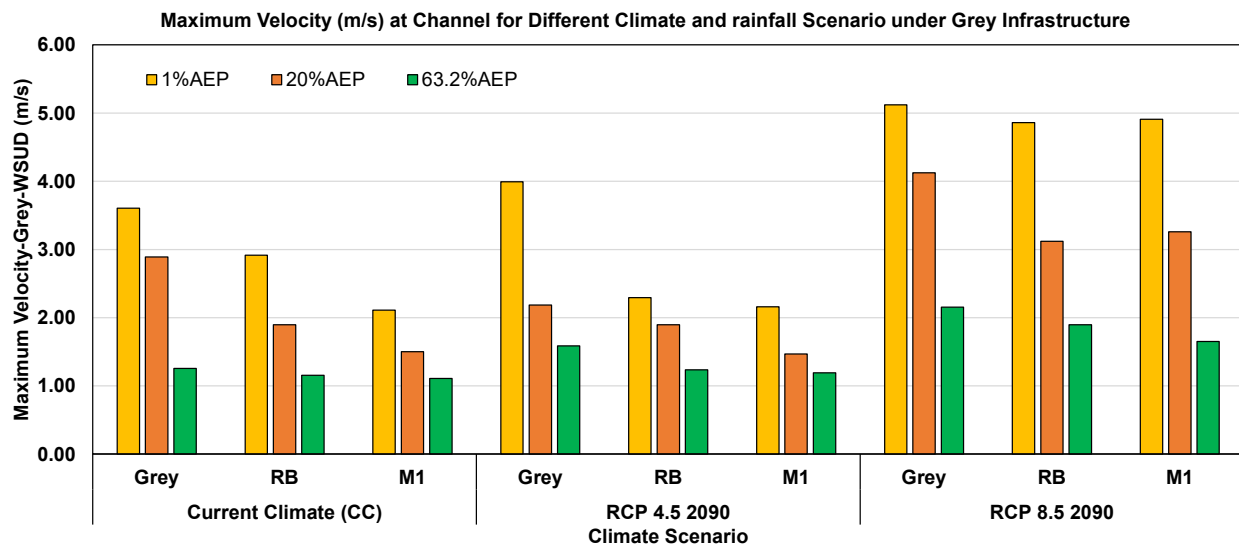


Figure 9. Engineers Park maximum velocity variation under CC, RCP 4.5 in 2090, and RCP 8.5 in 2090 with grey and best WSUDs (rain barrel and M1) with 100% effective impervious area.

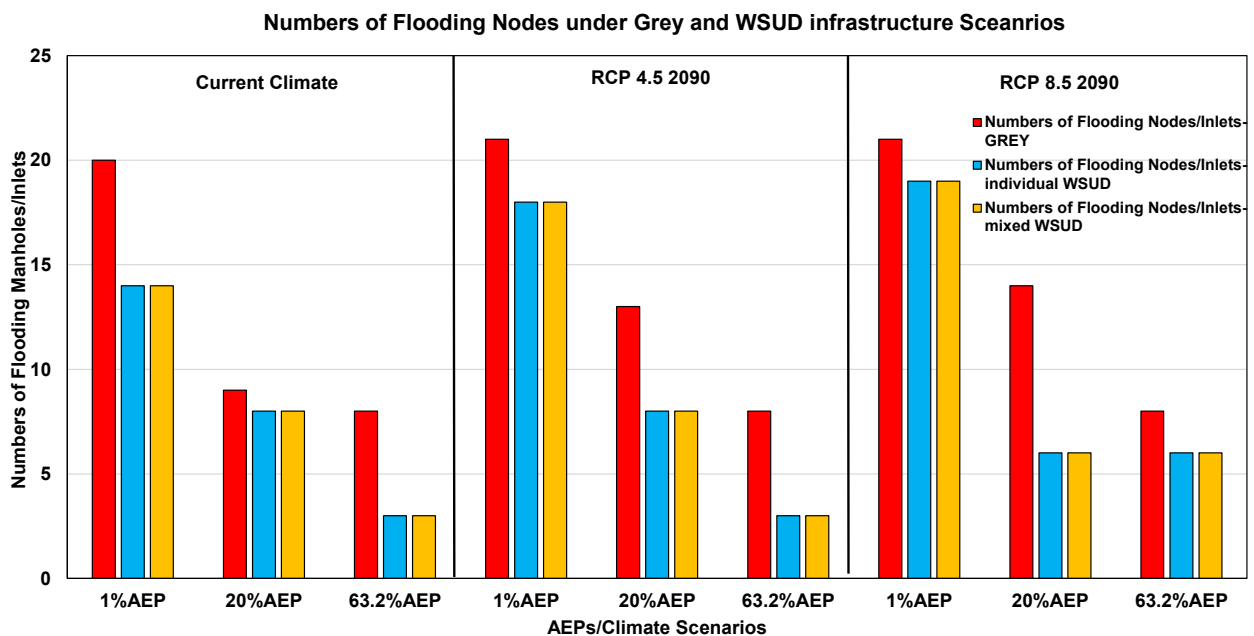


Figure 10. Engineers Park nodal flooding under CC, RCP 4.5 in 2090, and RCP 8.5 in 2090 with grey and best WSUDs (rain barrel and M1) with 100% effective impervious area.

The flood extent area-to-catchment area (FEA/CA) ratio, ranging from 1% to 8% across scenarios, serves as a key indicator of flood mitigation efficiency (Figure 11). A sharp increase in this ratio was observed during major rainfall under future climate scenarios (RCP 4.5 and 8.5 in 2090), while it remained relatively stable during minor and moderate events (Figure 11). WSUD integration significantly improved runoff management by intercepting direct flows from impervious surfaces and routing them to inlets, effectively reducing flooded nodes, overland flow, and inundation depths. Overall, WSUD reduced the FEA by 22–26% under the current climate and by 18–54% under RCP 8.5 in 2090, with the most notable reductions during major rainfall events.

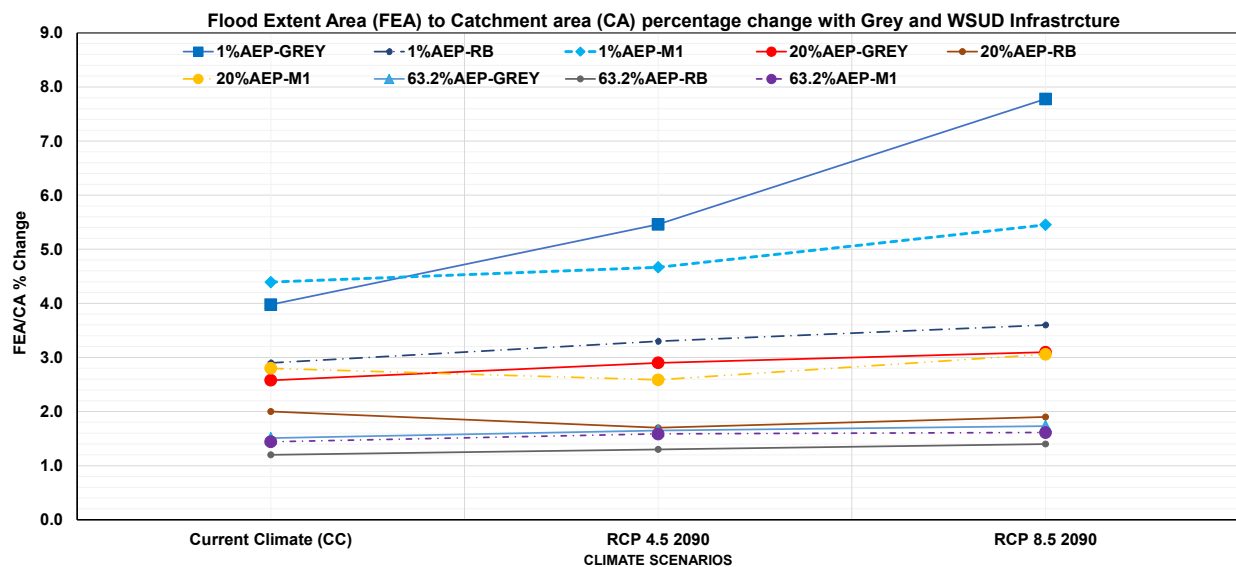


Figure 11. Engineers Park flood extent area (FEA) and catchment area (CA) under CC, RCP 4.5 in 2090, and RCP 8.5 in 2090 with grey and best WSUDs (rain barrel and M1) with 100% effective impervious area.

4. Discussion

4.1. Flood Mitigation Under Climate Change Scenarios

Even in a small catchment, projected increases in rainfall depth under climate change can have critical impacts, suggesting that compact urban areas may face significant hydrological stress. The findings indicate that existing grey infrastructure may become overwhelmed, particularly during moderate and minor events, not just major storms. Under future climate scenarios, runoff volumes are likely to exceed design capacities, leading to surface flow accumulation in low-lying areas, overspilling from culverts, and increased flood risks throughout the catchment. While grey infrastructure is effective at intercepting runoff, this also accelerates water movement, reduces infiltration, and contributes to flash flooding, especially downstream.

The study area, located in the steep upper reaches of the Saltwater Creek catchment, experiences rapid runoff due to a sharp elevation drop, increasing the risk of high-velocity flows and flash flooding in urbanised zones. Although prolonged inundation is unlikely, fast-moving water poses serious safety hazards to pedestrians and vehicles. These results highlight the need for a more strategic and integrated flood management approach. Complementing grey systems with low-cost WSUD solutions—such as those that can be incorporated into residential gardens—offers an opportunity to improve local resilience and reduce flood impacts at the sub-catchment scale.

4.2. WSUD Performance Under Climate Change

Rainfall intensity, climate scenarios, and the degree of effective impervious area reduction influence the performance of WSUD in this study. This study confirms a linear relationship between effective impervious area reduction and WSUD effectiveness in mitigating peak flow and total runoff volume, up to a 40% effective impervious area reduction.

Optimal performance of the WSUD systems was observed when the effective impervious area was decreased by 40% and 60% compared to existing scenarios. The studies conducted in Genoa, Italy, with a Mediterranean climate, and in New Zealand, with a temperate climate, reported similar results [56,57]. While effective impervious area reductions of more than 40% were observed, peak flow and total runoff volume efficiency were non-linearly related to effective impervious area reduction during major events. During major

events, other parameters, such as the amount of runoff received by the system, antecedent moisture, soil infiltration, and retention capacity, play a vital role in WSUD performance. With climate change, the WSUD performance in decreasing peak flow and total runoff volume is expected to follow a non-linear trend, with increasing rainfall intensity.

The application of WSUD needs to be carefully assessed in the context of climate change scenarios. Under these scenarios, moderate and minor rainfall events can equally exacerbate flooding, like a major event. WSUD performance under high-emission scenarios has been observed to degrade by up to 50%. During climate change conditions, the WSUD performance does not follow a linear trend; thus, its performance becomes highly unpredictable. Alteration in the characteristics of rainfall events due to climate change decreases the reliability of WSUD flood mitigation efficiency.

4.3. WSUD Implementation in This Study Site

Different WSUD systems responded differently under various climate and rainfall conditions at this study site. At the study site, retention-based systems, such as rain barrels and porous pavements, are highly suitable. Additionally, infiltration-based systems, including bio-retention, rain gardens, and infiltration trenches, are least preferred due to limited performance. The fast-flowing water, governed by the catchment's topography, was the primary regulator impacting the suitability of infiltration-based systems due to the short time available to initiate the infiltration mechanism.

Therefore, incorrect selection of WSUD systems, without considering site-specific slope and soil properties, could lead to reduced performance or reverse effects on peak flow and total runoff volume. Thus, this finding underscores the importance of carefully considering local topography when selecting WSUD systems, as it can significantly reduce their performance. This finding is particularly valuable in tropical climates where high-intensity rainfall events are becoming more frequent. These findings underscore the importance of context-sensitive design and a comprehensive evaluation of multiple influencing factors when planning WSUD interventions.

The change in characteristics of moderate and minor events is critical for planning the WSUD system. Primarily, studies assume that WSUD systems are highly functional during such events, and their performance significantly reduces during major events. At the same time, the current research suggests that moderate and minor events, which cause the maximum increment, may lead to a serious flooding problem in the future, as severe as those caused by major events. Therefore, the WSUD's capability to cope with such events can positively contribute to reducing flooding in this catchment, as well as in the overall catchment.

By intercepting runoff from roofs, pavements, and streets at their source, WSUD systems reduce the amount of runoff entering the drainage network, resulting in lower peak flows, total runoff volumes, and overland flow along roadsides. On the other hand, WSUD intervention also reduced roadside flooding and water depth, lowering the risk to pedestrians and vehicles. At the catchment scale, reductions in total runoff and delayed peak flows may help mitigate flood severity and flashiness in downstream, low-lying areas. This dual benefit highlights WSUD as a key strategy for improving flood resilience at this study site. In general, the implementation of WSUD measures at the study site had a positive overall effect on flood mitigation across various climate change scenarios.

4.4. Incorporating Climate Change: Philosophical and Methodological Issues

Climate change impacts are evident in designed rainfall, including the type of rainfall, its frequency, intensity, and spatial and chronological distribution, antecedent moisture, and changes in sea level [30]. Ref [46] has proposed several philosophical and methodological

approaches to address such uncertainty, reflecting the evolving understanding of climate science and its implications for hydrology. Each method discussed, as shown in Table 6, has its strengths and weaknesses; however, none of the approaches thoroughly addresses the limitations. To overcome the uncertainty, this study employed an integrated, precautionary, scenario-based approach within the regional context, along with an adaptive management principles approach, to evaluate current flood mitigation measures and the potential of WSUD systems. The current study assessed the effectiveness of existing grey measures during three rainfall events under current and future climate change scenarios. The best available local data, obtained from the Cairns Regional Council and fieldwork, were utilised to establish the model setup, calibration, and validation phases. In addition, not only the existing measures but also proposed interventions using WSUD measures were evaluated. Although this is a time- and resource-consuming process, it can be an advantageous approach to reduce potential sources of uncertainty and improve the reliability of decision-making.

Table 6. Climate change incorporation: Philosophical and methodological approaches described in ARR, 2019 [46].

Philosophical Approaches	Salient Features	Strengths	Limitations
Precautionary principle	Adoption of rainfall increase factors	Reduces the risk of underdesign	Can lead to overdesign and economic burden
Scenario-based	Range of future climate scenarios (representative concentration pathways—RCPs)	Resilient and flexible system	Laborious, time-consuming, complex, and leads to an ambiguous decision
Risk-based approach	Design based on the criticality of assets	Aligns with consequences	Data- and expertise-intensive
Regional context	Methods adjusted and adopted are specific to the localised context	More accurate and relevant	Challenges due to limited data in many regions
Adaptive management	Interactive planning	Sustainable long-term	Complex to institutionalise

Climate change evaluations generally rely on long-term historical records of temperature, rainfall, evaporation, and sea level rise [17]. Although estimated rainfall data is available, it often lacks the spatial and temporal accuracy essential for direct flood modelling. To address this constraint, [31] proposed a method that leverages more reliable temperature projections to estimate rainfall changes under future climate scenarios. Thus, this study adopted temperature climate data to assess the impact of climate change on rainfall.

4.5. Challenges of WSUD Implementation in the Tropics

The implementation of WSUD in the tropics is more challenging than in other regions, such as arid or temperate regions, for several reasons. Tropical areas are characterised by high temperatures, high humidity, and extreme rainfall [11]. Repetitive, intense storm events in this region result in a high volume of runoff, which is further increased by rapid population growth and the presence of impervious areas due to rapid urbanisation. To deal with such high-flow scenarios, the grey measures adopted must be of considerable size to accommodate the extra flow. Constructing and maintaining such large grey measure systems is challenging and requires a high economic investment. Thus, integrating WSUD measures provides an alternative option to deal with such challenges. However, it is not straightforward to integrate WSUD in the tropics; the selection of vegetation is critical to

the successful implementation, as rapid plant growth results in intensive costs for repair and maintenance. A study conducted in a tropical region assessed the life cycle cost of a vertical greenery system, observing that approximately 74% to 84% of the cost was invested in the operation and maintenance of this system [58]. Limited funds to maintain these systems can result in locations becoming a high-risk hotspot for mosquito breeding, posing a significant health risk to the people residing there. Therefore, before the extensive adoption of such measures, critical maintenance plans need to be developed and practised. Finally, one of the significant challenges to the comprehensive adoption of these measures is the limited number of studies and considerable policy and guideline gaps that have been developed specifically for these regions, which also impact the implementation of WSUD in tropical areas.

5. Limitations and Future Research

The WSUD modelling approach adopted during this study showed promising results. However, one significant limitation of these results is the lack of validation of the WSUD model results. Currently, this study site does not have any WSUD implemented and lacks field-measured data from the inflow and outflow of the WSUD systems to further validate the results. On the other hand, model calibration and validation were conducted using a limited dataset. Furthermore, the constant urbanisation assumption under climate change scenarios is another limitation of this study. Since this study focused on understanding the sole impact of climate change, it assumes constant urban growth, which can also affect the current performance of WSUD systems. However, our results can serve as a preliminary guide for the future application of such measures in tropical regions and further validate the current findings.

Future research should focus on how flooding patterns change in response to climate change, including the effectiveness of existing flood mitigation measures at the catchment scale. The impact of climate change on WSUD performance needs to be assessed. Most of this study focuses on the WSUD site-scale contribution; however, future research should also examine its catchment-scale implications and the suitability of centralised or decentralised application approaches.

6. Conclusions

This study evaluated the performance of grey infrastructure and WSUD systems in mitigating flooding under various rainfall intensities and climate change scenarios in a tropical urban catchment.

Under the future climate change scenarios, grey infrastructure alone proved inadequate for managing an increased flood risk. In contrast, integrating WSUD with grey infrastructure significantly improved flood mitigation outcomes. WSUD implementation reduced peak flow, total runoff volume, node flooding, and the flood extent ratio across all climate and rainfall scenarios.

The study suggests a critical need to evaluate the role of grey measures in urban flood management. Future urban flood mitigation and adaptation approaches must be able to cope with future greater water volumes to address the challenges posed by climate change effectively. This result implies that the increase in peak flow and total runoff volume under future climate change was evident for all AEPs, exacerbating the flood risk under all rainfall conditions. While WSUD demonstrated clear potential for enhancing flood resilience in this tropical catchment, the performance of some WSUD systems may be limited by excessive runoff received by the WSUD system, steep terrain, soil properties, or design constraints. Combining multiple WSUD options during this study helps to overcome these limitations, but careful evaluation of individual system performance is required before integration.

The long-term effectiveness of WSUD depends on the development of site-specific designs that address localised context-specific climate adaptability and integrate them into broader flood management planning frameworks. Overall, WSUD integration represents a valuable complement to grey infrastructure in tropical urban settings; however, careful interpretation of the results is required, considering its limitations, and additional assessment is necessary to evaluate performance at the catchment scale and in other different types of flooding scenarios, such as compounding flooding.

Author Contributions: Conceptualisation, S.B.G. and B.J.; data collection and modelling works, S.B.G.; investigation, S.B.G.; resources, S.B.G.; writing—original draft preparation, S.B.G.; writing—review and editing, S.B.G., B.J., R.J.W., and M.B.; visualisation and supervision, B.J., R.J.W., and M.B. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The field data used in this study are available from the corresponding author upon request.

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Conflicts of Interest: The authors declare that they have no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviations	Meanings
WSUD	Water-Sensitive Urban Design
AEP	Annual exceedance probability
1D	1-dimensional
2D	2-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
ARR	Australian rainfall and runoff
IFD	Intensity frequency duration
RORB	Runoff routing

DHI	Danish Hydraulic Institute
GIS	Geographic information system
PP	Porous pavement
RB	Rain barrel
BR	Bio-retention
EIA	Effective impervious area
RG	Rain garden
IT	Infiltration trench
VS	Vegetated swale
TBF	Tree box filter
FEA	Flood extent area
CA	Catchment area
QGIS	Quantum Geographic Information System
MWL	Maximum water level
GHGs	Greenhouse gases
RCPs	Representative concentration pathways
CC	Current climate

Appendix A

Flood inundation maps with grey and WSUD measures.

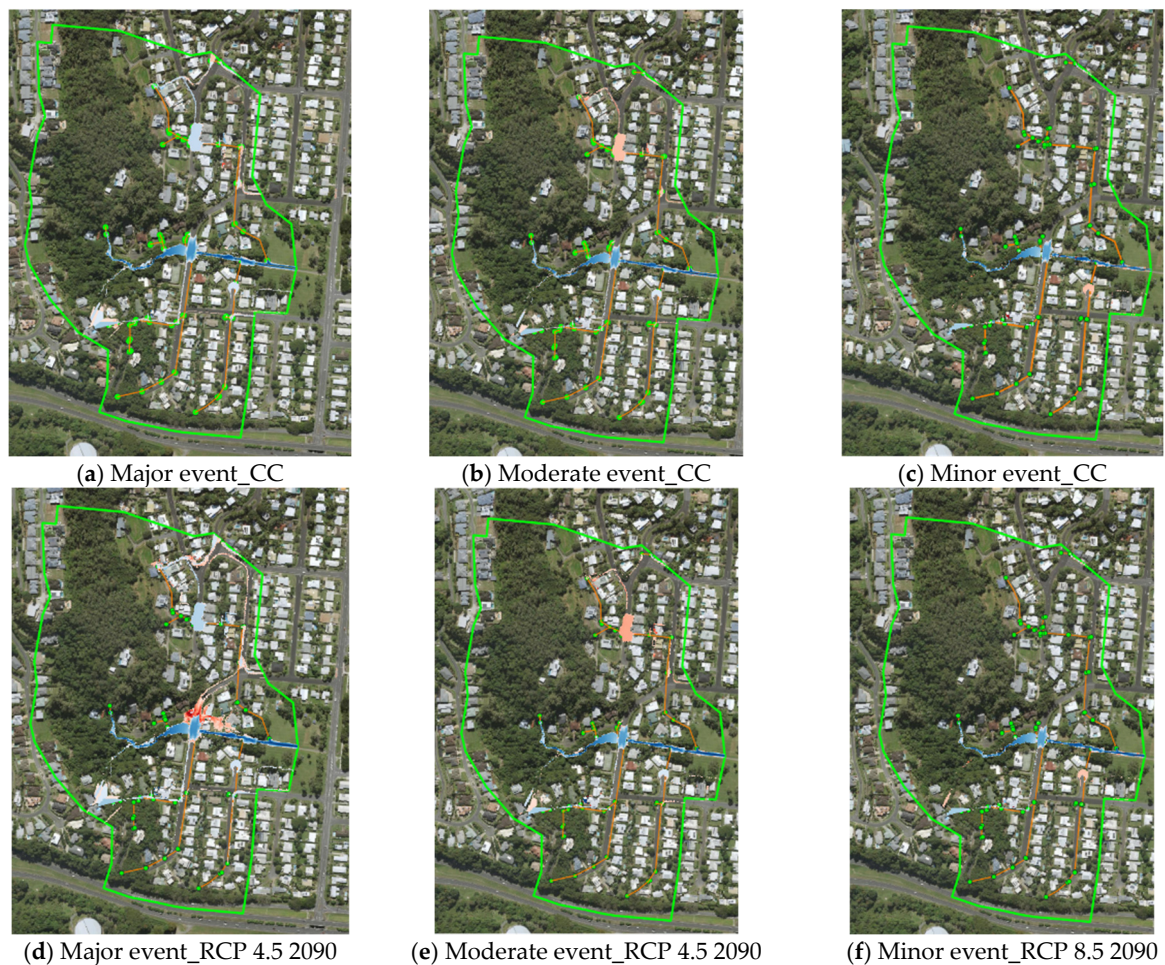


Figure A1. *Cont.*

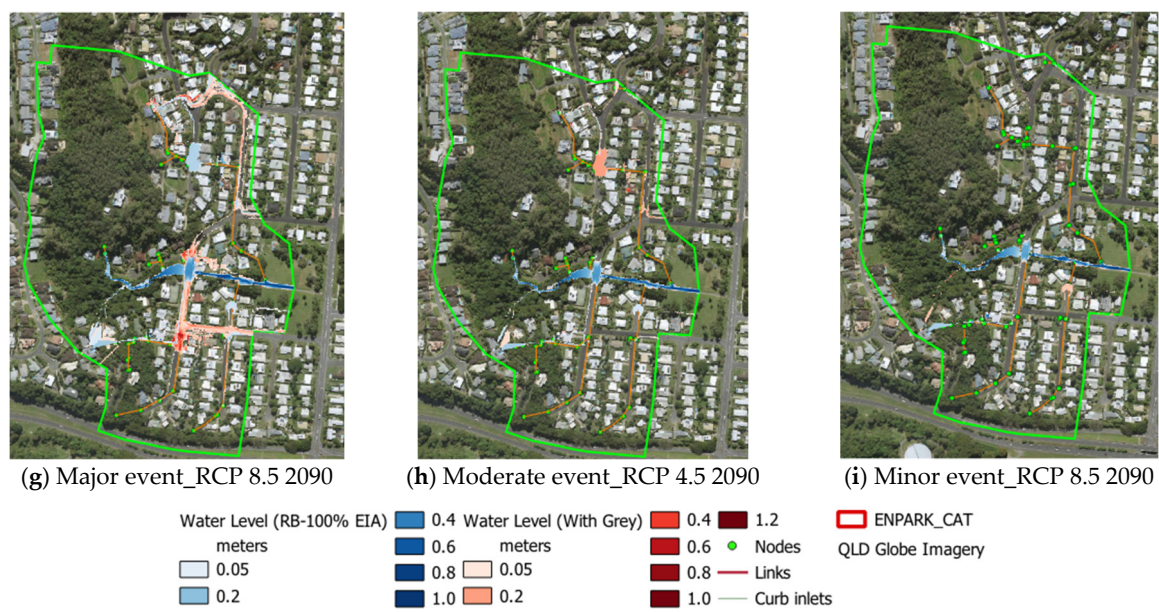


Figure A1. Flood maps under CC, RCP 4.5 2090, and RCP 8.5 2090 with grey and best-performing individual WSUDs with 100% EIA reduction.

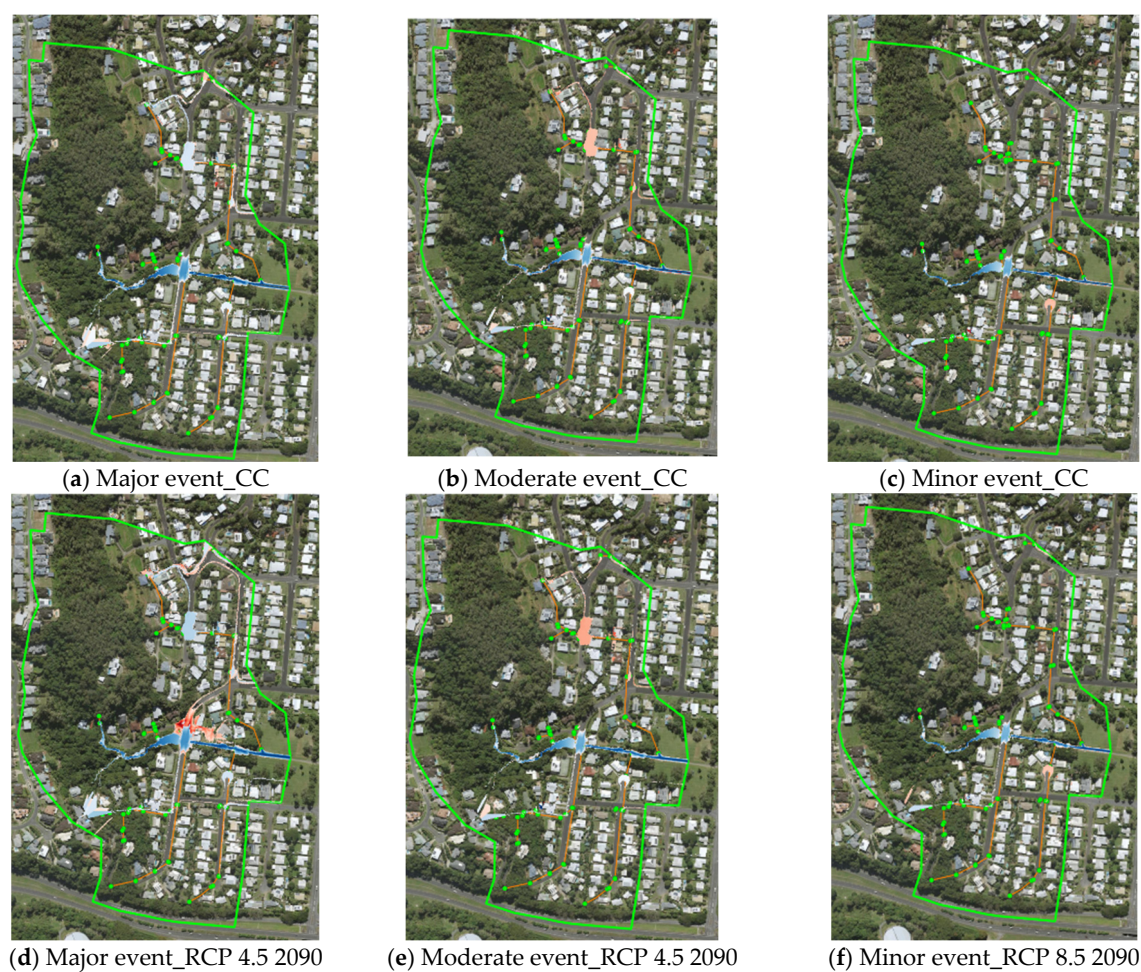


Figure A2. *Cont.*

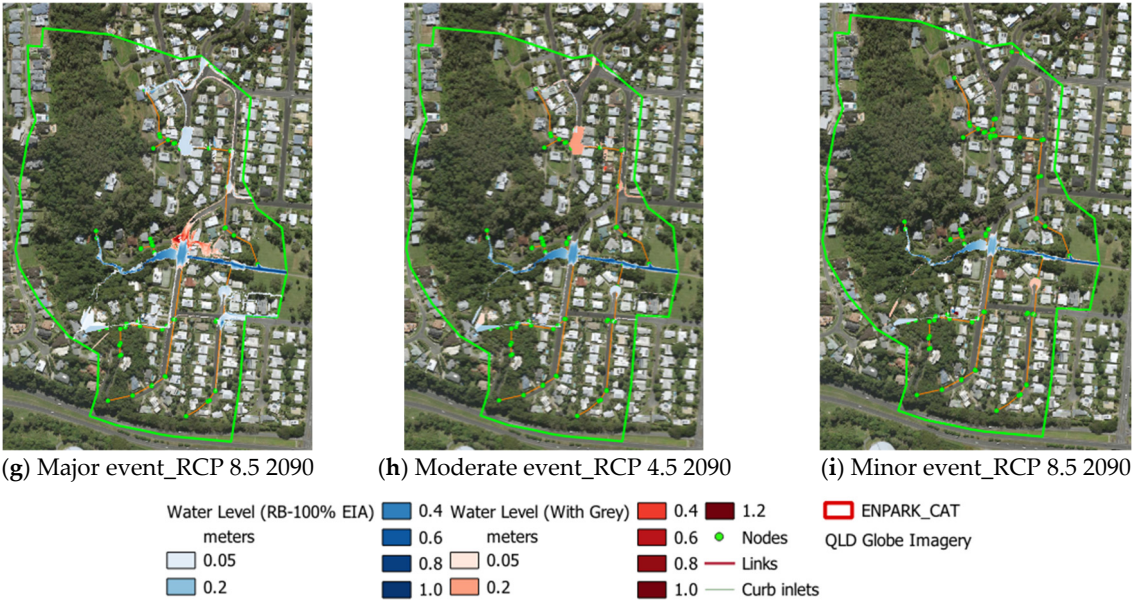


Figure A2. Flood maps under CC, RCP 4.5 2090, and RCP 8.5 2090 with grey and best-performing mixed WSUDs (M1) with 100% EIA reduction.

Table A1. WSUD parameters incorporated into MIKE+ modelling [29,53,55,58].

Parameters	Bio-Retention	Rain Garden	Rain Barrel	Infiltration Trench	Porous Pavement
Surface					
Berm height (mm)	1000	1000 (100–1000)		200	100 (100–1000)
Vegetative cover	0.7	0.7		0	0
Surface slope (%)		1		1	1
Surface roughness (m ^{1/3})/s	0.1	0.1 (0.1–0.15)		0.1	0.1 (0.1–0.15)
Soil infiltration capacity (mm/h)	1	10–140		-	-
Swale side slope (rise/run)		-		-	3–4
Soil					
Field capacity	0.31	0.31		0.31	0.31
Wilting point	0.09	0.09		0.09	0.09
Flow capacity (leak capacity/infiltration capacity/h)	1.5	1.5		-	-
Infiltration capacity (mm/hr)	50	50			
Conductivity	5	1.5		-	-
Conductivity, conductivity slope, suction header	49.5	5–105		-	-
Pavement					
Thickness	-	-		-	150
Porosity	-	-		-	0.21
Permeability	-	-		-	3000
Impervious surface	-	10–70		10–70	0
Storage					
Height (mm)	300	-	900	500	250
Porosity	0.3	-		0.35	0.9
Conductivity	300	-		300	1000
Clogging factor	0	-		0	0
Drain		-		-	

Table A1. *Cont.*

Parameters	Bio-Retention	Rain Garden	Rain Barrel	Infiltration Trench	Porous Pavement
Offset height (mm)	200	-	300	200	200
Delay (h)	-	-	0.5	0.5	-
Exponent	0.5	-	0.5	-	0.5
Drain capacity (per area mm/h)	50	-	50	50	50
Drain coefficient	-	0–120		0–20	-

Table A2. Average peak flow reduction for different WSUD systems under current and climate change scenarios.

Rainfall Design Events	PP	RB	BR	RG	IT	M1	M2	M3	M4	M5
Mean peak flow reduction (%) under the current climate										
Minor	32	34	21	22	28	33	31	28	28	29
Moderate	24	25	13	14	19	24	23	19	19	21
Major	20	22	9	12	15	21	21	17	16	17
Mean peak flow reduction (%) under RCP 4.5 2090 scenarios										
Minor	30	32	18	20	26	31	29	26	25	8
Moderate	23	24	11	12	17	23	22	18	17	19
Major	19	21	6	9	14	19	20	15	14	16
Mean peak flow reduction (%) under RCP 8.5 2090 scenarios										
Minor	28	30	15	17	24	29	24	22	22	26
Moderate	21	22	9	10	16	22	17	15	15	18
Major	18	20	6	7	12	18	14	12	12	15

Table A3. Average total runoff volume reduction for different WSUD systems under current and climate change scenarios.

Rainfall Design Events	PP	RB	BR	RG	IT	M1	M2	M3	M4	M5
Mean total runoff volume reduction (%) under the current climate										
Minor	38	39	27	30	35	39	36	34	34	36
Moderate	30	31	19	22	26	30	27	26	25	27
Major	23	25	13	16	20	24	22	20	19	21
Mean total runoff volume reduction (%) under RCP 4.5 2090 scenarios										
Minor	36	37	27	28	33	36	34	32	32	33
Moderate	28	29	20	20	25	29	26	24	24	25
Major	22	23	14	14	18	22	20	18	18	20
Mean Total runoff volume reduction (%) under RCP 8.5 2090 scenarios										
Minor	34	35	25	26	32	34	31	30	30	32
Moderate	27	27	17	17	23	27	23	22	22	23
Major	21	22	13	12	17	21	18	16	16	18

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