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The Use of PCSWMM for Assessing the Impacts of Land Use Changes on Hydrological Responses and Performance of WSUD in Managing the Impacts at Myponga Catchment, South Australia

Muhammad Saleem Akhter and Guna Alankarage Hewa *

School of Natural and Built Environment, University of South Australia, Mawson Lakes 5095, Australia; akhmy006@mymail.unisa.edu.au

* Correspondence: guna.hewa@unisa.edu.au; Tel.: +61-8-830-23094

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Abstract: Personal Computer Stormwater Management Model (PCSWMM) was applied to investigate: (1) hydrological responses in the Myponga catchment as a result of land use changes; and (2) the possibility of adopting Water Sensitive Urban Design (WSUD) technologies (bio-retention cells) to manage resulting floods. Calibrated and validated models predicted the measured data with satisfactory accuracy and reliability. Different urbanization scenarios were tested. When the level of urbanization increased from 10% to 70%, mean discharge increased from 45% to 322%. Frequency of flood at 2-year Average Recurrence Interval (ARI) increased from 1 to 44 and frequency of floods at 100-year ARI increased from none to 8. At 70% urbanisation, trialled bio-retention facilities used as WSUD measures almost completely ameliorated 2-year ARI floods by reducing the frequency of such events from 44 to 2. Floods at smaller ARIs (2, 5, 10 and 20 years) were effectively managed by WSUD measures while floods at 50- and 100-year ARIs remained unchanged. The overall results improve understanding of the severity of the impacts of land use changes on the hydrology of a catchment and the ability of bio-retention cells to alleviate the risk of small to medium floods in the Myponga catchment.

Keywords: Myponga; catchment; PCSWMM; land use changes; floods; WSUD; bio-retention cells

1. Introduction

Rapidly growing populations are adversely impacting water resources at both a local and global scale. Urbanization is expanding in order to accommodate the increasing populations. The transition of a natural catchment into an urbanized catchment results in many environmental impacts. According to Elga et al. [1] urban development is considered to be a source of pollution for water resources, while increasing flooding and threatening both people's safety and the integrity of infrastructure on a broader scale. Du et al. [2] found that urbanization reduces infiltration, base flow and lag times, as well as increasing stormwater flow volumes, peak discharge, frequency of floods and surface runoff. The severity of all these hydrological impacts can be dependent on the degree of urban development within a catchment [3]. The impacts of urbanization on the environment, in particular hydrological processes like flooding of a catchment, need to be quantified in order to set limitations on levels of permissible urban development [4].

The assessment of land use change on hydrological responses is one of the current areas of interest in hydrological modelling. Hydrological models are tools that help to predict the impact that land use changes (with varying development scenarios), will have on flow regimes [5]. Mao and Cherkauer [6] used Storm Water Management Model (SWMM) to study land use change responses in the upper

Midwestern United States and concluded that deforestation increased runoff by 30% to 40% in the central part of the study area. The Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) and the integrated Markov Chain and Cellular Automata model (CA-Markov model) were used to investigate runoff from land use changes in the USA and it was concluded that when impervious ratios changed from 3% to 31%, daily peak discharge increased from 2.3% to 13.9% [2].

South Australia is the driest state in the Australian continent and the Myponga catchment is situated south of the South Australian capital, Adelaide. Urbanization in South Australia has increased during the last few decades and many catchments are being transformed from natural to urbanized. The Myponga catchment, in particular, has experienced significant land use change during recent years [7]. Wella-Hewage [8] reported that 75% of the Myponga catchment area was used for cattle and sheep grazing in 2002 but this decreased to 69% in 2014. Residential use increased from 4% to 24% during the same period. These land use changes have increased the risks of flooding in the vicinity of Myponga Reservoir. The impact of land use change needs to be examined in order for sustainable development to occur, thus minimizing the impacts on humans and water resources.

SWMM has been a widely accepted tool for modelling the hydrological processes of a catchment. SWMM was first developed in 1971 in the USA by the Environmental Protection Agency (US EPA) and since then has been continuously upgraded. The latest version is SWMM 5—which includes a graphical interface—is widely used across the globe for dynamic rainfall runoff modelling for a single event or continuous quantity and quality modelling for both urban and rural catchments [9]. Currently, SWMM is used for planning, design, analysis and management related to storm water quantity, combined sewers, sanitary sewers, and other drainage systems in urban areas, however it is also applicable in rural catchments for water quality modelling [10]. SWMM is a catchment scale model and provides an integrated environment for editing input data for a given study area and results can be viewed in a number of formats [11]. Several studies have utilized SWMM, including Lee [3], Sun, Hall, Hong and Zhang [11], Wella-Hewage [8], Abdul-Aziz and Al-Amin [12] and Yu et al. [13], for low flow studies, catchment discretization, Water Sensitive Urban Design (WSUD) methodology development, runoff and pollutant modelling and drainage system analysis, respectively. Though the model has numerous advantages and has a wide range of applications, it does not have any spatial interface. Therefore a commercially available advanced model PCSWMM was developed in 1984 with a Geographic Information System (GIS) linkage to provide a comprehensive range of applications [14]. PCSWMM is a combination of GIS and US EPA SWMM 5 and provides a scalable and complete package for 1D and 2D analysis of rainfall runoff processes [14]. PCSWMM has comprehensive river modelling tools, real-time control analysis, time series management, Digital Elevation Model (DEM) support, native GIS support, automated reporting and Google Earth visualization for hydrology, hydraulics and water quality modelling. PCSWMM also has the ability to model storm water source control technologies to manage water quantity and quality [9]. Stormwater source control techniques are referred to as WSUD in Australia, Low Impact Development (LID) in the US, Sustainable Drainage Systems (SuDS) in the UK and Low Impact Urban Design and Development (LIUDD) in New Zealand. Therefore, PCSWMM was adopted for this study to investigate the impacts of urbanization on the hydrological responses of the Myponga catchment. Additionally, WSUD technologies were investigated in order to determine if they were capable of minimizing impacts in relation to flood control and water management.

2. Methodology

2.1. Study Area, Data and Model Conceptualization

The Myponga catchment is located about 60 km south of the city of Adelaide at the southern end of the Mount Lofty Ranges. The main channel originates from the south-eastern side of the catchment, discharging into the Myponga Reservoir and is known as Myponga River [15]. The whole catchment covers an area of 122 km^2 and drains to a flow gauge station (A5020502) upstream of the Myponga reservoir as shown in Figure 1a [7]. According to Barnett and Rix [16], the sedimentary aquifers in the

Myponga catchment are comprised of Tertiary Limestone, Permian Sands and Quaternary sediments. Sand and loamy sand are the dominant soil type in the catchment. Figure 1b depicts major land use in the Myponga catchment. The main land use is livestock which includes broad scale grazing for sheep and cattle. Grazing accounts for almost 69% of catchment land use and includes cropping, modified pasture and silage. During the summer season, ground water is pumped for irrigation purposes in the catchment [16]. The population of rural residents is increasing and residential and commercial land use has continued to increase, becoming the second major land use type in the catchment. About 24% of the catchment was used for residential and commercial activities in 2014, which is almost six times that reported in 2002 (4%) [8]. A floodplain modelling study done in the vicinity of Myponga Reservoir found that flow in the Myponga River at or above 1.97 m^3/s (167.65 mL/day) caused flooding in the area [17].

The Department of Environment, Water and Natural Resources (DEWNR) [7] manages the gauge station upstream of Myponga Reservoir. Average stream flow at the upstream gauging station is 7500 mega-litres per year (mL/year) while Myponga Reservoir has a capacity of 26,800 mL. According to the Bureau of Meteorology BOM [18], the average temperature in the Myponga catchment varies from a minimum of 11 °C to a maximum of 27 °C in summer and from 5 °C to 18 °C in winter. Mean annual rainfall and evaporation are approximately 677 mm and 985 mm, respectively. Variations in mean monthly rainfall, evaporation and runoff can be observed in Figure 2.

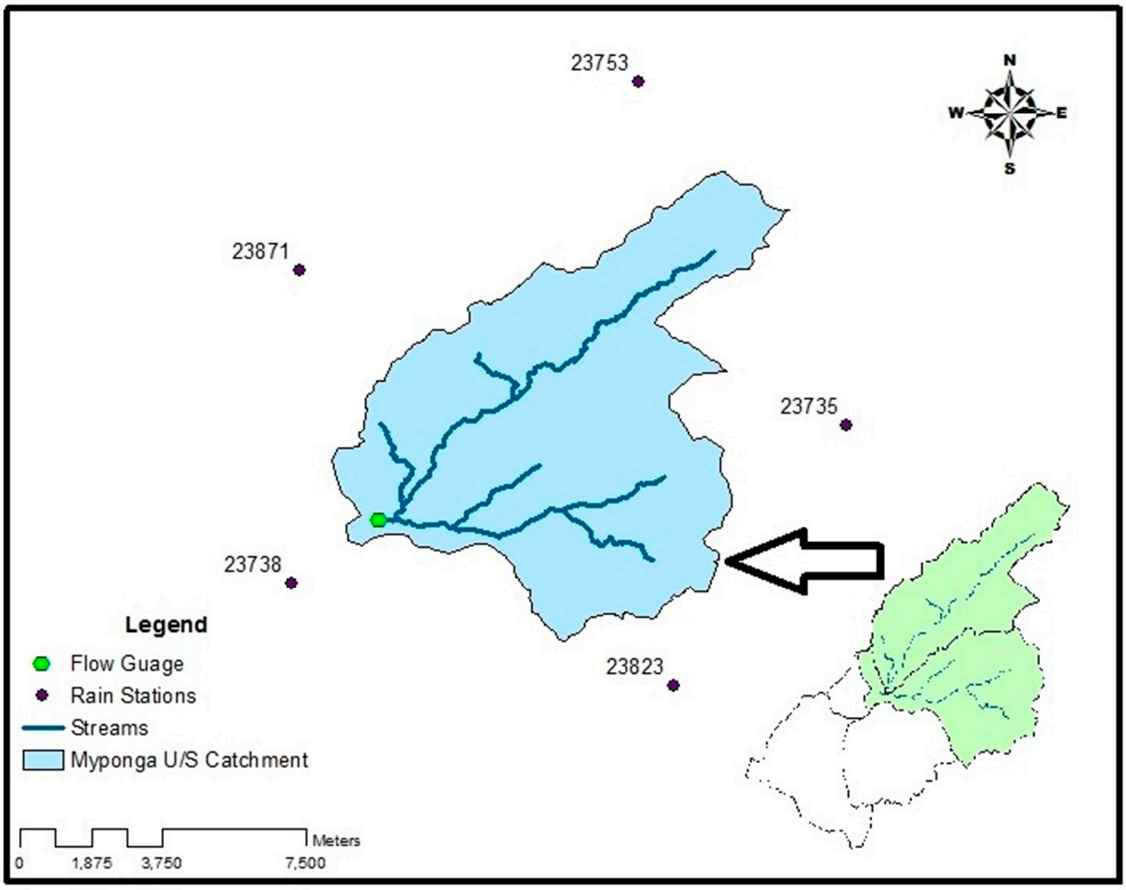

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Figure 1. *Cont.*

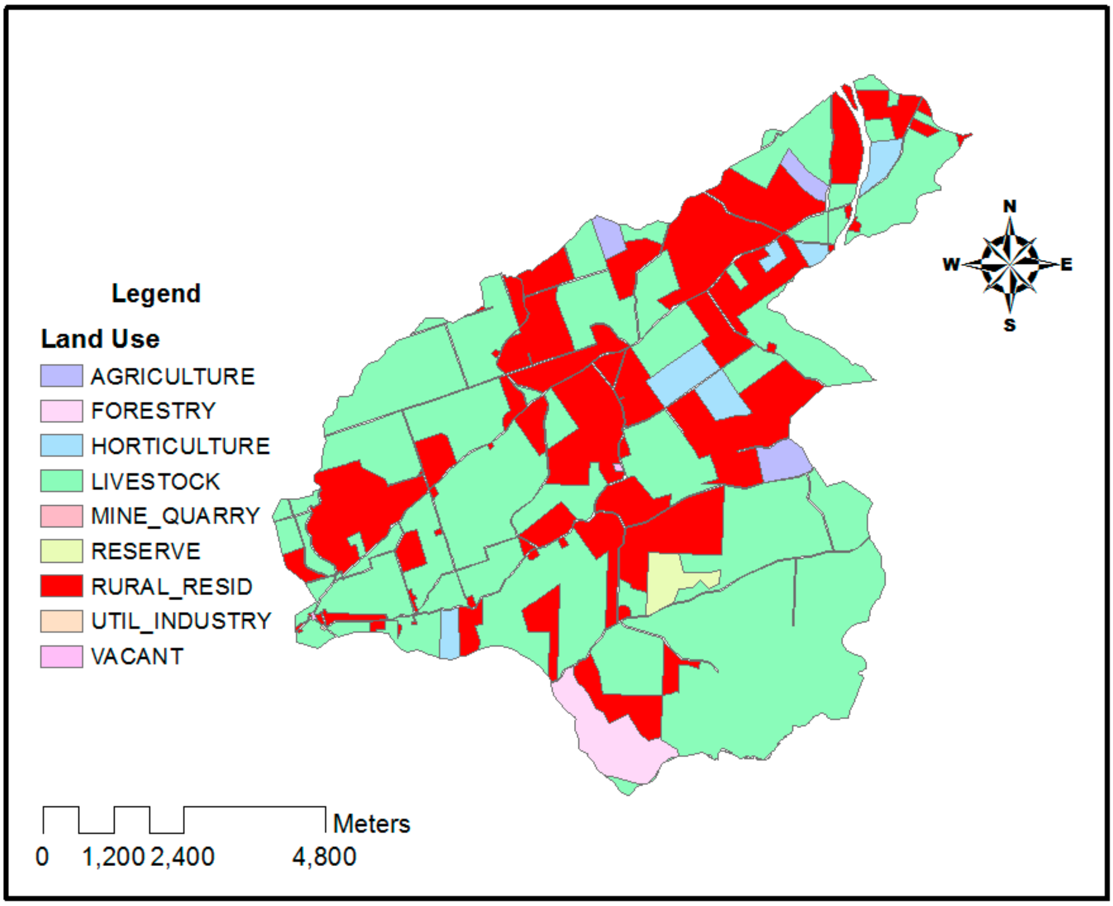

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Figure 1. (**a**) Myponga upstream (U/S) catchment with meteorological stations; (**b**) Major land uses in the Myponga upstream catchment.

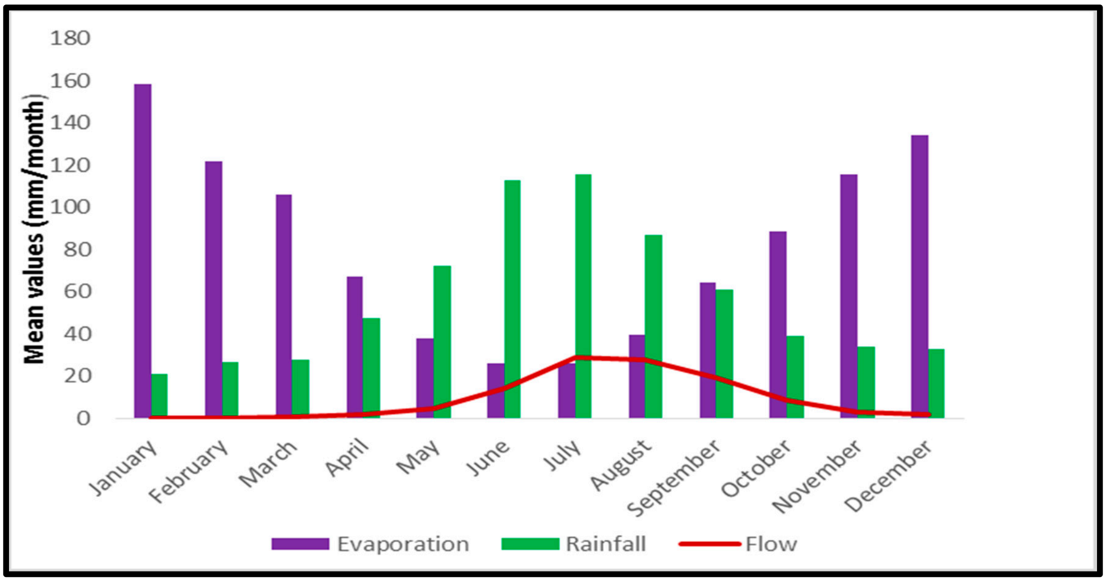

Figure 2. Mean monthly evaporation, rainfall and flow in the Myponga upstream catchment.

In PCSWMM, the rainfall runoff process is conceptualized using material and water flow between its environmental sectors. All the processes can be assigned into four compartments: atmospheric compartment; land surface compartment; transport compartment; and ground water compartment. The atmospheric compartment requires rainfall and evaporation data. For this study rainfall data for five selected stations and evaporation data for one station were obtained from BOM [18]. Catchment weighted average rainfall for the Myponga catchment was computed using the Thiessen Polygon method. Although the measured flow data at gauge station A5020502 were available from 1980 to 2014 rainfall data were not available for all 35 years as some rain gauges were removed or relocated. Therefore, the period between 2005 and 2014 was adopted for model calibration (2005–2010) and validation (2011–2014) purposes. Hydrologic and land use data required for the land surface compartment were extracted from a GIS database obtained from DEWNR [7]. The transport compartment requires junctions and conduits for the stream network that were retrieved from DEM data. The ground water compartment required aquifer and ground water data which were not readily available. However, soil types and water table levels were gathered from DEWNR [7] and Barnett and Rix [16] and the remaining parameters were gained through model calibration using default initial values. The catchment delineation tool from PCSWMM was used for catchment delineation from DEM data and then discretised into sub-catchments. Finally, 28 sub-catchments were created with conduits and junctions, while the reservoir was treated as an outfall, as shown in Figure 3. The impervious percentage for each sub-catchment was calculated using sub-catchment layers and land use layers through catchment conceptualization.

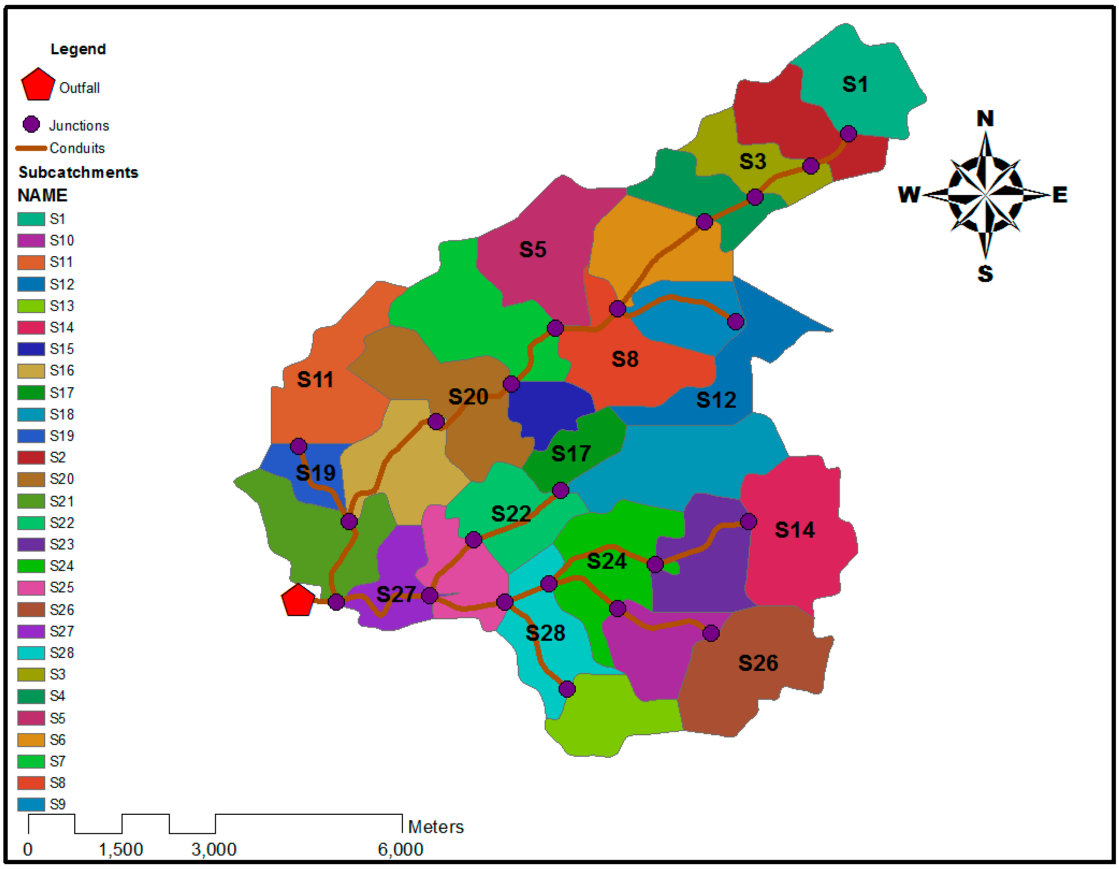

Figure 3. Catchment discretization for modelling.

2.2. Myponga PCSWMM Calibration and Validation

In order to make reliable model predictions, the most suitable model parameters were selected through a model calibration procedure. PCSWMM uses Sensitivity-based Radio Tunning Calibration

(SRTC) or a knowledge based calibration system. The calibration process starts with the selection of initial parameter values along with specified uncertainties in PCSWMM. Choi and Ball [19] categorized the control parameters into two types, measured parameters and inferred parameters. Among the measured parameters, catchment areas, rainfall depth and pipe diameter were included. While the inferred parameters are not directly measured but estimated by model, these include catchment width, Manning's roughness coefficient and depression storage. However, the selection of parameters for calibration depended upon model performance and the uncertainties in data input files. After assigning the initial parameter values to all the model parameters, the uncertainty of each parameter was assigned based on their data source, as reported by James [20]. The assigned uncertainty values help to redefine the mean, using the upper (V_{Upper}) and lower (V_{Lower}) limits of the parameters as calculated using the following formulas [21]:

$$V_{Upper} = V_{Current} \times (1 + V_f) \tag{1}$$

$$V_{Lower} = V_{Current} \times \left[\frac{1}{(1 + V_f)}\right] \tag{2}$$

where

$V_{Current}$ = Value of pre calibration parameter used in PCSWMM;

V_f = Fraction representing the percentage of variability calculated for the range.

Based on James' [20] suggestion for SRTC, selected parameters for calibration were assigned the uncertainties presented in Table 1.

Table 1. Calibration parameters and assigned uncertainties in PCSWMM.

Compartment	Notation	Calibration Parameter	Uncertainty Value (%)
Land surface	Area	Sub-catchment area	10
	Width	Sub-catchment width	100
	Imperv. %	Impervious percentage	25
	Dstore Perv	Depression storage for pervious area	50
	Dstore Imperv	Depression storage for impervious area	50
	N perv	Manning's roughness for pervious area	25
	N Imperv	Manning's roughness for impervious area	25
	Max. Infl. rate	Maximum infiltration rate	50
	Min. Infl. rate	Minimum infiltration rate	50
	Decay constant	Decay constant	
	Dry time	Dry time	50
Transport	Geom 1	Geometry and maximum depth of conduits	25
	Roughness	Manning's roughness of conduits	25
Ground water	A1	Ground water flow coefficients	100
	B1	Ground water flow exponents	100

As noted in Section 2.1, though the measured flow data was available at the gauge station A5020502 for the past 35 years, rainfall data was not available for full period. Therefore, the period between 2005 and 2014 was used for the PCSWMM modelling of the rainfall runoff process in the Myponga catchment. Rainfall and flow data for 2005–2010 and 2011–2014 were used for calibration and validation respectively. The calibration and validation periods were treated as dry and wet years respectively, in the water calendar. It has been found that the model performs better if it is calibrated for dry years and validated for wet years [22,23]. The measures used for assessing the performance of PCSWMM during calibration and validation are the Nash-Sutcliffe coefficient (NS), Relative Error (RE) (%) and Coefficient of Determination (R^2). NS and RE (%) are calculated as follows:

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}^{n} (Q_i - Q_i')^2}{\sum_{i=1}^{n} (Q_i - Q_{avg})^2} \tag{3}$$

where

NS = Nash-Sutcliffe coefficient (a measure of model efficiency);
Q_{avg} = average daily discharge for the simulation year or simulation season;
Q_i = measured daily discharge;
n = number of daily discharge values;
Q'_i = simulated daily discharge.

$$\mathrm{RE}(\%) = \frac{(Q_o - Q_s)}{Q_o} \tag{4}$$

where

RE (%) = difference between the total measured and simulated runoff;
Q_s = simulated runoff;
Q_o = measured runoff.

2.3. Urbanization Scenarios and WSUD Technologies in PCSWMM

The present condition of the catchment was taken as the base line for the study and is referred to as the "Present Scenario", with the imperviousness calculated through model conceptualization. All the sub-catchments were assigned zero imperviousness in the case of the "Natural Scenario". Seven future urbanization scenarios were hypothetically generated: 10%; 20%; 30%, 40%; 50%; 60%; and 70% urbanization. Each selected scenario was applied to every sub-catchment and hence the percentage imperviousness within every sub-catchment was increased accordingly from the Present Scenario. The calibrated and validated PCSWMM model was used as a tool to simulate the urbanization scenarios. The hydrological effects of the urbanization scenarios were assessed using Flow Duration Curves (FDC), mean discharge (Q-mean) and Flood Frequency Curves (FFC). FFCs were developed using Log Pearson Type III (LP III) distributions fitted to 35 years of the annual maximum series in order to investigate flood risks at the downstream end of the Myponga catchment.

WSUD technologies such as rain gardens, green-roofs and various kinds of rain barrels were modelled in PCSWMM, with the control of stormwater primarily managed through processes associated with storage and evapotranspiration. The other type of system, which includes measures such as bio-retention cells, vegetative swales, permeable pavements, leaky-wells and wetlands, controls stormwater through infiltration, storage and evapotranspiration. Systems in the latter category are known as "infiltration-based WSUD systems" and are increasingly used for stormwater management in Australia. Bio-retention cells are widely used to control the runoff peaks and volumes of storm water [24–26]. Therefore, bio-retention cells were modelled to minimize the risks of flooding due to increased urbanization. Surface, soil, storage and underdrain parts of bio-retention cells require different types of data. The data include berm height, vegetative volume, slope, thickness, porosity, wilting point, hydraulic conductivity, seepage ratio, drain coefficients and suction head [10,27]. Much of the data, including slope, porosity, wilting point, hydraulic conductivity and seepage ratio, were retrieved from available data layers, while other data were based on published values.

3. Results

3.1. Prelimiary Analysis of Historical Data

Land use in the Myponga catchment has dramatically changed over the last decade. The impact of this change on runoff is evident in the trend in runoff compared to rainfall shown in Figure 4. Despite the fluctuations observed in annual rainfall and annual runoff, the general trends are positive. The growth rate of annual runoff trend in Myponga is quite strong compared to that of annual rainfall.

If it is assumed that climate change impact has not been significant within this short span of time, the observed trends suggest that land use change might have increased the fraction of impermeable surface area within the catchment, resulting in increased runoff volume and flow magnitudes. Hence, the current condition of the catchment cannot be assumed to be "natural".

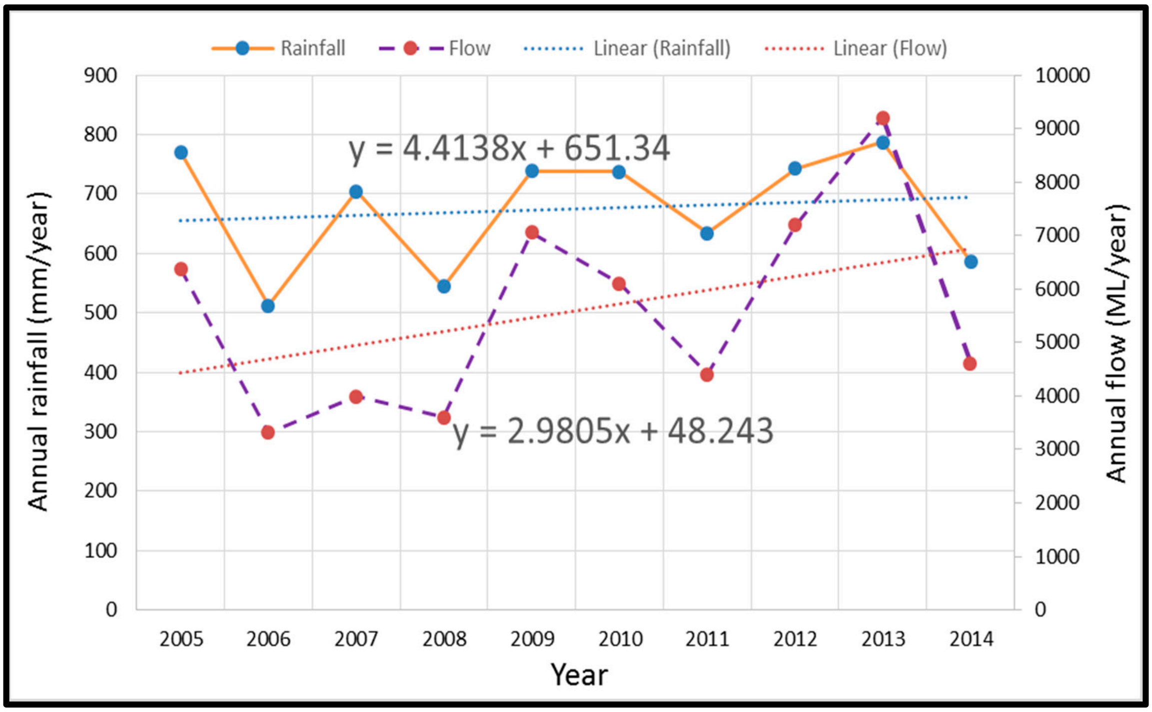

Figure 4. Rainfall and flow trends within the modelling period for the Myponga catchment.

3.2. Parameter Sensitivity Analysis in SRTC

The calibration parameters were checked using SRTC within the assigned sensitivities to determine the effect of parameter change on runoff. Of the 10 parameters listed in the land surface compartment, only impervious percentage, sub-catchment width, depression storage for impervious area and minimum infiltration rate were sensitive within the specified range. Therefore, all the insensitive parameters were left unchanged from their initial values, while the sensitive parameters were adjusted frequently until the best set of parameters was achieved. Sub-catchment width and percentage impervious area were the most sensitive parameters in the land surface compartment, with depression storage and minimum infiltration rate mostly impacting low flows. With the ground water compartment having only one sensitive parameter (minimum infiltration rate) it was apparent that the optimization process for the Myponga model is mainly governed by surface water related parameters. This can be explained in terms of the nature of the catchment, where the ground water table is quite low and therefore surface water is the main source of flow. As a result of the understanding gained through this sensitivity analysis, the value of depression storage for impervious area was increased from 1.90 mm to 3.80 mm for all the sub-catchments after calibration. Similarly, the minimum infiltration rate value was increased to 3.04 mm/h from the initially assigned value of 1.52 mm/h for all the selected 28 sub-catchments.

3.3. Model Performance during Calibration and Validation

Figure 5a,b visually compare the modelled and observed flow series for the Myponga outfall during calibration and validation for the complete as well as selected time periods. There is good agreement between the observed flow time series and the modelled flow time series. The assessment of model performance merely based on these visual observations was not sufficient, hence some other comparative measures were adopted. Table 2 presents relative error values at peak flows, mean flows and total flow volumes for both the calibration and validation periods. Overall R^2 and NS values for both the calibration and validation periods are also given. During calibration, maximum peak flow had only 17% relative error. Mean flow and total volume were found to be predicted more accurately with only −6.25% and −11% relative errors. The minus indicates that the model has overestimated the flow during simulation. The values of R^2 and NS of 0.57 and 0.51 also confirmed a satisfactory model calibration. The relative errors of mean flow and total volume improved for the validation period, dropping to 5% and 4.65% respectively. The higher values of R^2 and NS (0.63 and 0.57 respectively) when compared to results from the calibration period, supports the use of the developed model for the current study.

Table 2. Model performance during calibration and validation periods.

Action	Duration	Peak Flow			Mean Flow			Total Volume			R^2	NS
		Observed m^3/s	Simulated m^3/s	RE (%)	Observed m^3/s	Simulated m^3/s	RE (%)	Observed mm^3	Simulated mm^3	RE (%)		
Calibration	2005–2010	7.75	6.35	17	0.16	0.17	−6.25	30.45	33.98	−11	0.57	0.51
Validation	2011–2014	6.44	7.65	−18.8	0.2	0.19	5	25.39	24.21	4.65	0.63	0.57

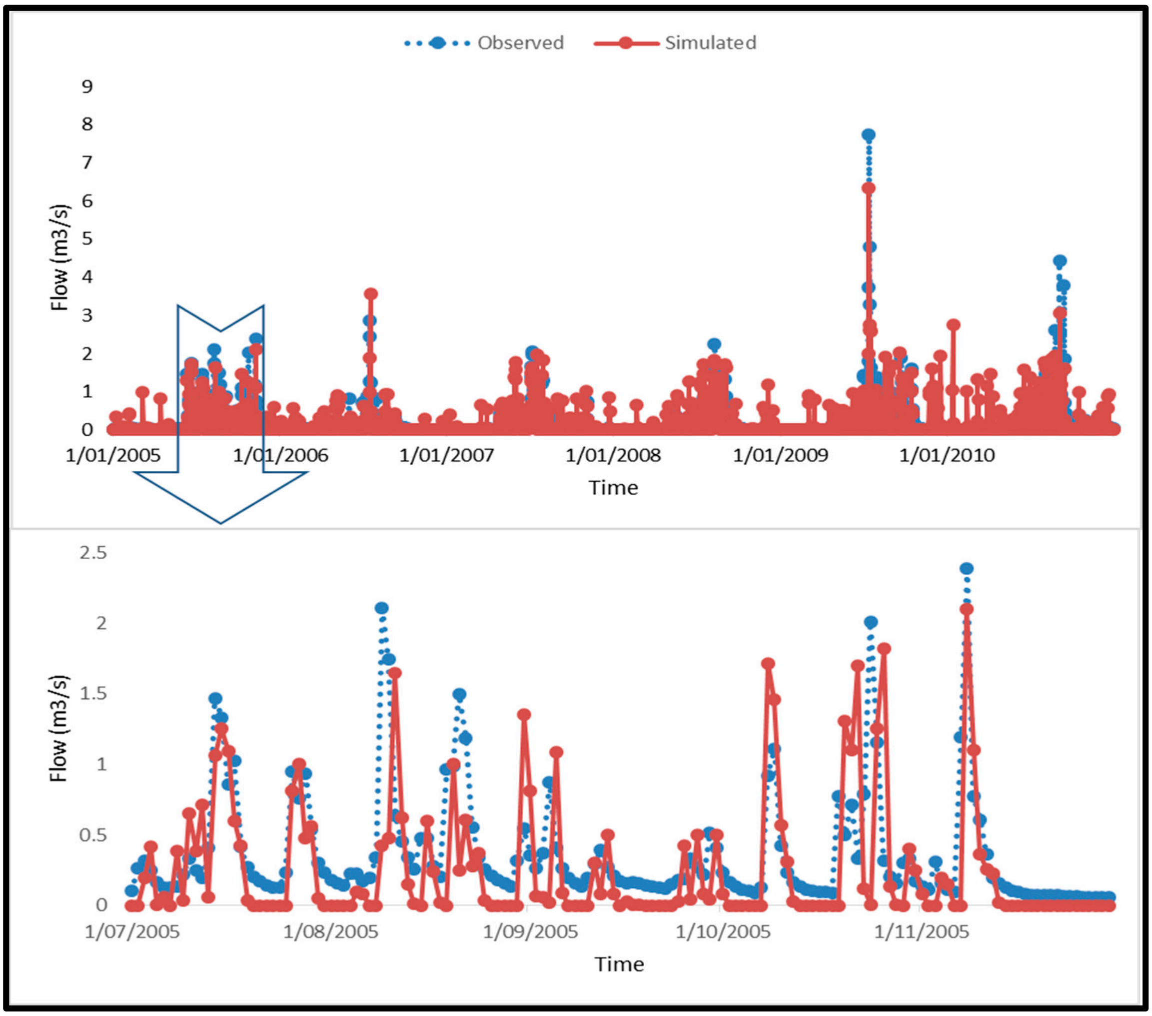

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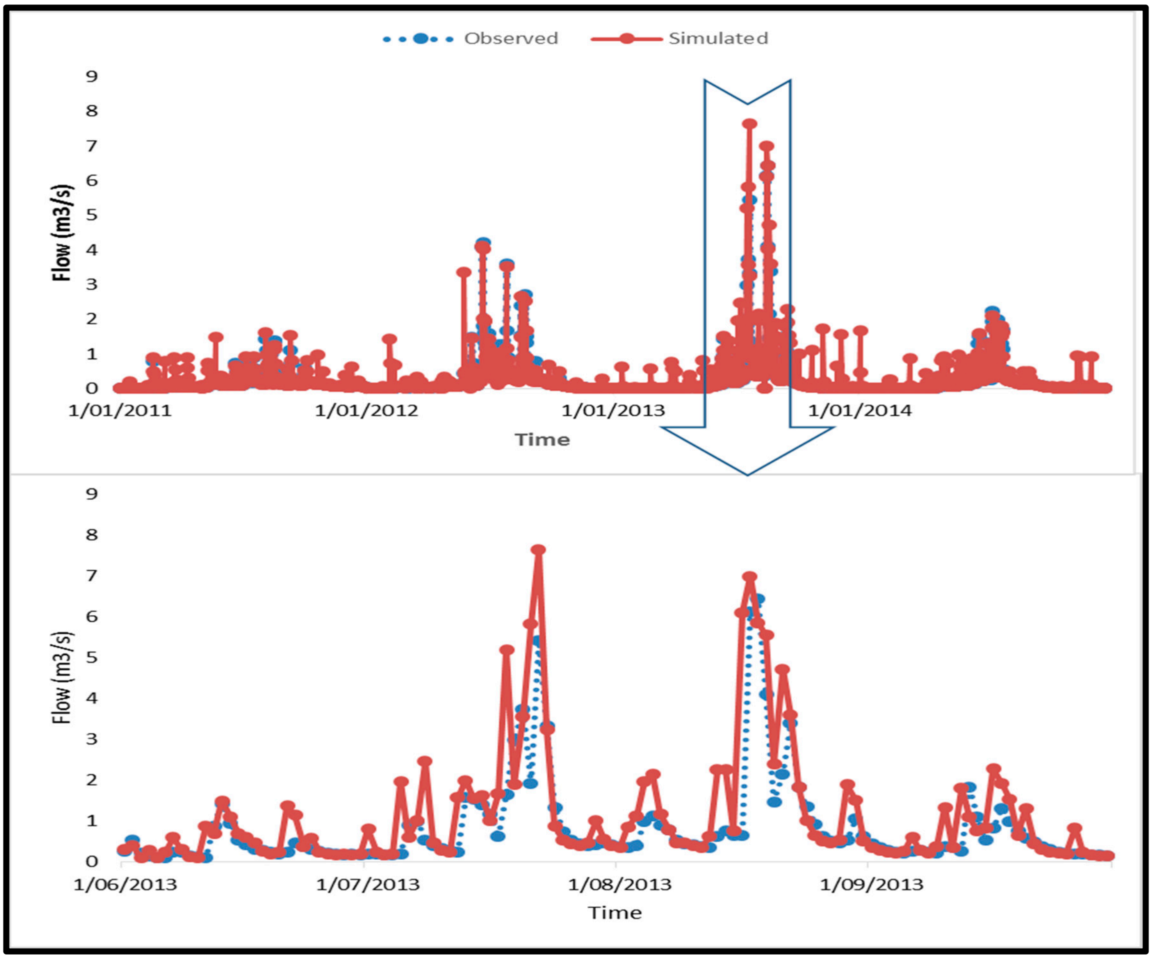
Figure 5. *Cont.*



(**b**)

Figure 5. (**a**) Comparison of the simulated and observed flow series during calibration; (**b**) Comparison of the simulated and observed flow series during validation.

3.4. Quantification of Urbanization Impacts

3.4.1. Hydrological Impacts of Urbanization Based on FDC

Urbanization impacts on FDC indices are shown in Figure 6. The graphs indicate a continuous increase in high flows along with a continual decrease in low flows, as the urbanization percentage is increased. The "natural scenario" does not produce an FDC. This could be due to the rainfall input to the catchment infiltrating into the soil or being stored on the surface as depression storage. It could also be partly due to the fact that all the land is covered by natural vegetation or forests and hence zero imperviousness may result. High rates of interception as a result of natural forests in the catchment and subsequent evapotranspiration might also contribute to this result.

Figure 6 also indicates that the FDCs end with flows that are exceeded less than 25% of the time, indicating that base flow and groundwater contribution to total streamflow is negligible. This could be due to the fact that, as noted earlier, the catchment has a very low groundwater table. It can also be observed that when urbanization is increased to 70%, extreme flows that are exceeded 10% of the time increase from 6.44 m^3/s to 35 m^3/s. This illustrates the severe impacts of urbanization leading to increased flooding potential in the catchment.

Figure 7 demonstrates how flow hydrographs change as urbanization increases from present condition to 20%, 40% and 70% urbanization. It is apparent that urbanization intensifies all of the flow peaks, with each peak flow growing as the urbanization percentage increases. The highlighted area shows that the impact of land use change is quite prominent even for a small event.

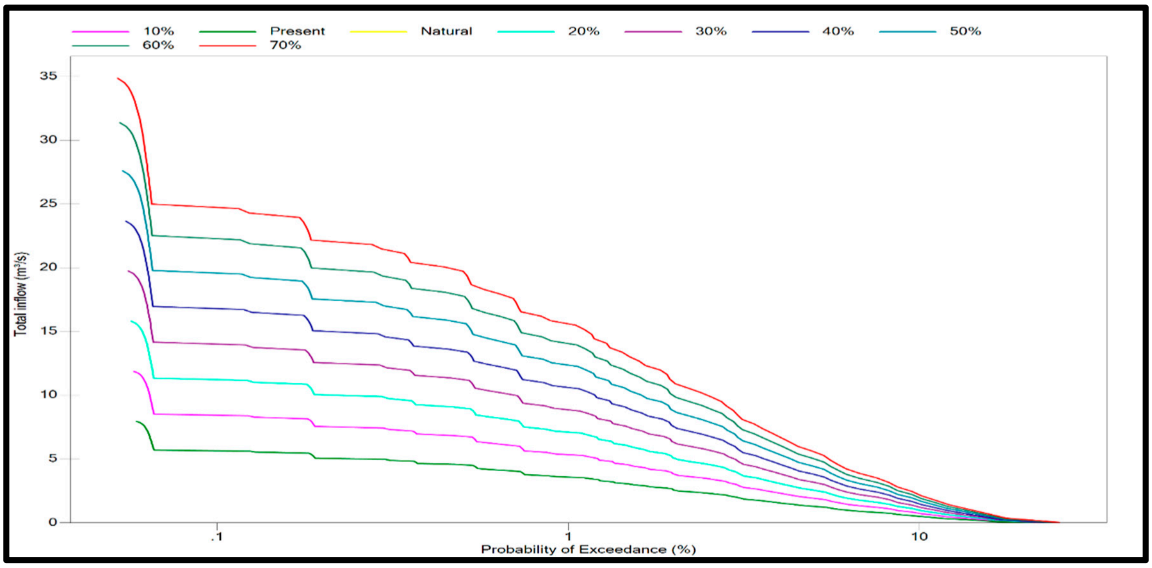


Figure 6. Effects of urbanization on Flow Duration Curve (FDC) in the Myponga catchment.

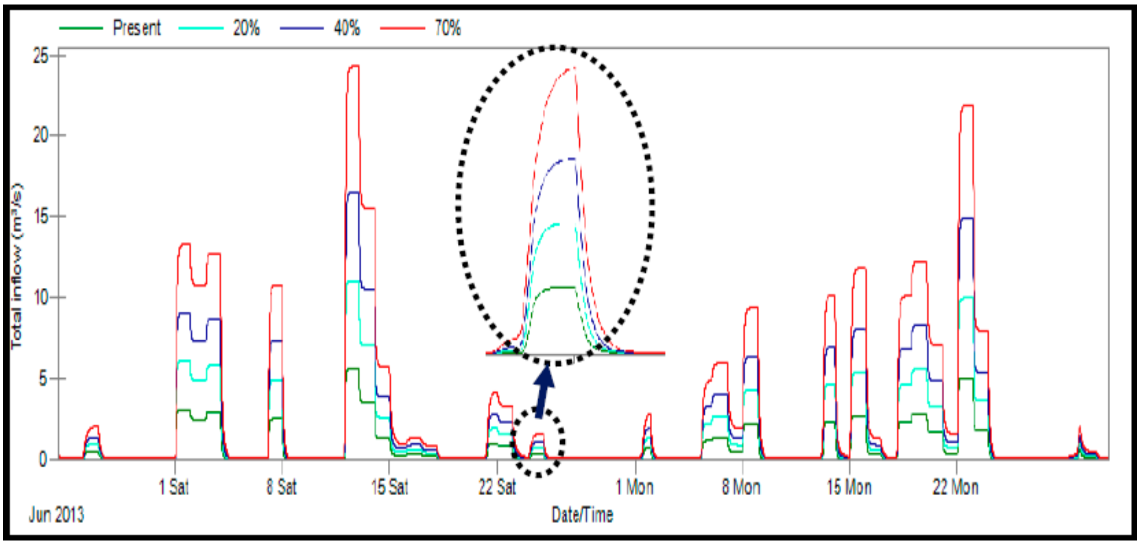


Figure 7. Urbanization effects on individual hydrographs.

3.4.2. Impacts of Urbanization on Q-Mean

Q-mean is an indication of average stream conditions. The mean flow in the Myponga catchment increased from 0.29 m^3/s to 0.84 m^3/s as urbanization increased from present level to 70% urbanization level. Overall Q-mean increased from 45% to 322% when urbanization increased from 10% urbanization to 70% urbanization (Figure 8). There was an increasing trend in the mean flow and the increase could be the result of increased overland flow as urbanization reduces infiltration. These changes in mean flow can cause deterioration in stream conditions and new channels could be formed, leading to new floodplains and ultimately problems for local residents and industries. Wella-Hewage [8] concluded that increases in mean flows lead to deterioration in channel banks and ultimately new flood plains are generated. Bledsoe and Watson [28] found that urbanization also led to the destabilization of river banks as a result of increased runoff and mean flows.

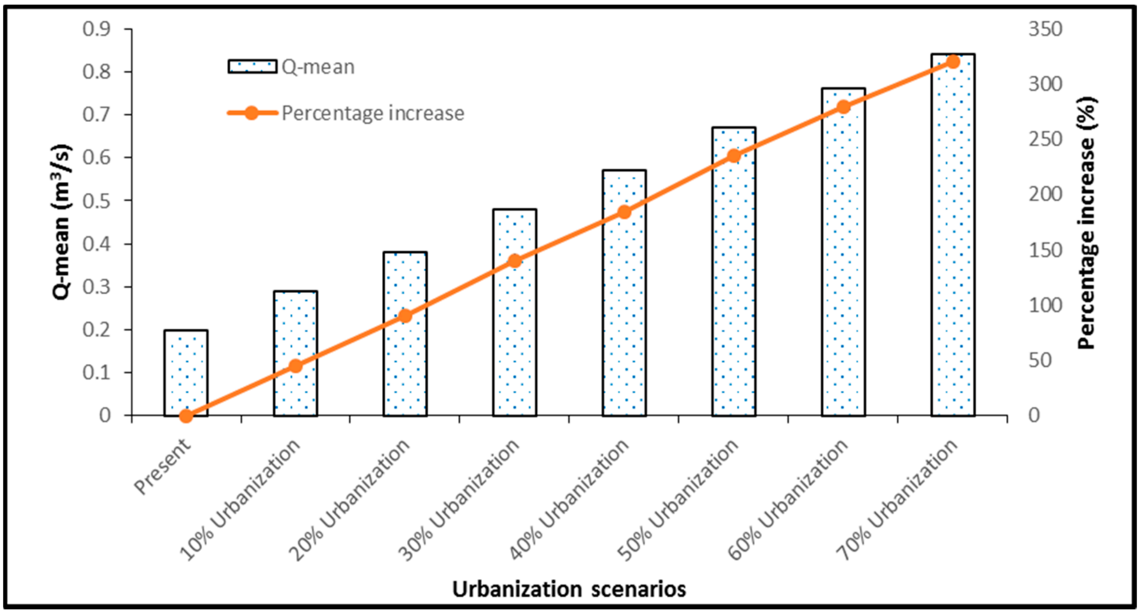


Figure 8. Urbanization effects on mean daily flow.

3.4.3. Impacts of Urbanization on Flood Frequency Statistics

The Annual Maximum (AM) series analyses of the Myponga gauge station data were conducted using a LP III distribution to quantify flood quantiles (Q_T) at six selected Average Recurrence Intervals (ARIs): 2; 5; 10; 20; 50; and 100 years. The estimated flood quantiles are presented in Figure 9 along with a probability plot constructed using Cunnane's plotting position formula [29]. The 95% Upper Confidence Limit (UCL) and 95% Lower Confidence Limit (LCL) were also computed to demonstrate the acceptable range of flood quantiles. It can be clearly observed from Figure 9 that the fitted LP III curve closely describes the observed data at low to medium ARIs, while a greater deviation occurs at higher ARIs. However, all the LP III estimated floods quantiles are within the UCL and LCL.

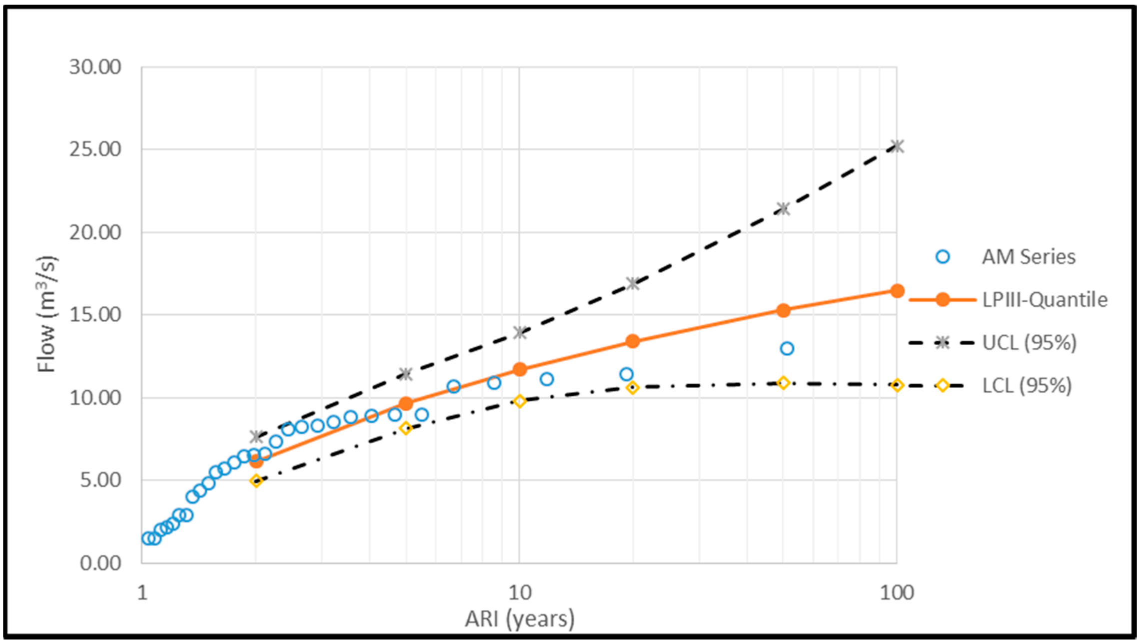


Figure 9. Flood frequency curve (FFC) for the Myponga catchment. ARI: Average Recurrence Interval; AM: Annual Maximum; LP III: Log Pearson Type III; UCL: Upper Confidence Limit; LCL: Lower Confidence Limit.

The estimated flood quantiles at the six selected ARIs were then used as threshold values to determine how frequently the flood quantiles are exceeded when urbanization is increased. These results are presented in Figure 10. The frequency of flood at 2-year ARI increased from 1 to 44 as the level of urbanization increased from present levels to 70%. However, the same increase in level of urbanization only results in an increase in the frequency of a flood at 100-year ARI from none to 8 times. This observation indicates that frequent floods occur almost three times more often when the percentage of urbanization in the Myponga catchment increases from 10% to 70%. Therefore, it was found that urbanization in the Myponga catchment would be expected to increase the frequency of flooding and, most importantly, the number of frequent floods would rise significantly as compared to extreme floods.

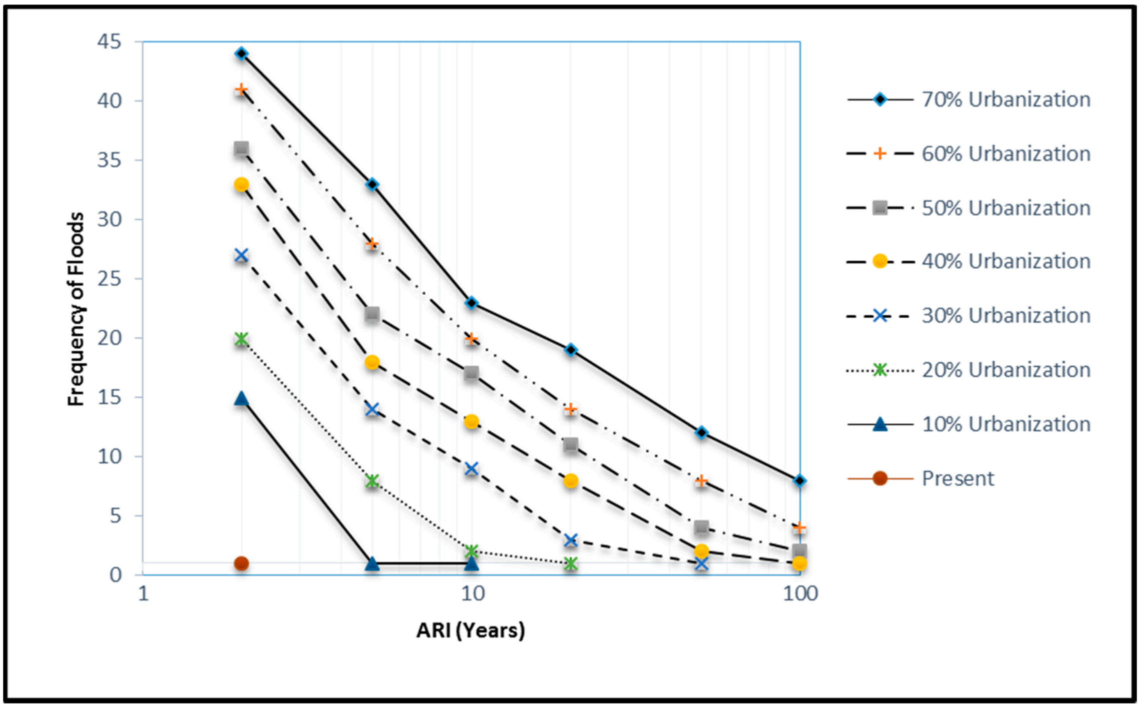
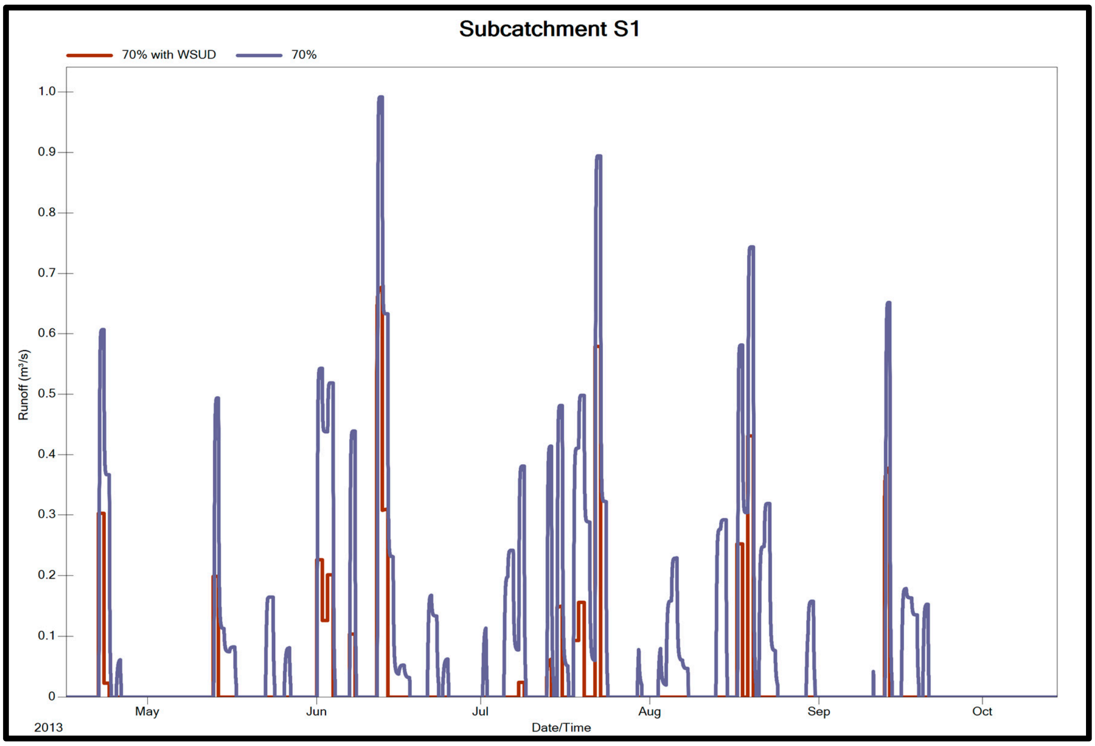


Figure 10. Effects of urbanization on flood frequencies in the Myponga catchment.

3.5. WSUD Technologies; as a Flood Control Measure

WSUD technology, i.e., bio-retention cells, were designed and added to each of the sub-catchments in the Myponga catchment. Bio-retention cells were attached in such a way that all the runoff from both pervious and impervious areas were passing through them. For a given urbanization scenario, 100% impervious area of each sub-catchment was (managed) under the control of bio-retention. Results of PCSWMM model simulation for 70% urbanization with bio-retention cells at the end of the selected sub-catchment (S1, shown in Figure 3), and at the catchment outfall over selected time periods are presented in Figure 11a,b. Comparison shows there is a substantial decrease in the number of peaks observed in the sub-catchment. The peak flow decreased from 1.0 m^3/s to 0.67 m^3/s as a result of the bio-retention cell in S1, while there is approximately a 7 m^3/s reduction at the outfall. The 70% urbanization scenario resulted in many new small events in S1, which are totally removed by the WSUD technology. It is apparent that the bio-retention cells worked efficiently to control the peak flows and runoff volumes in S1 that were the result of urbanization.



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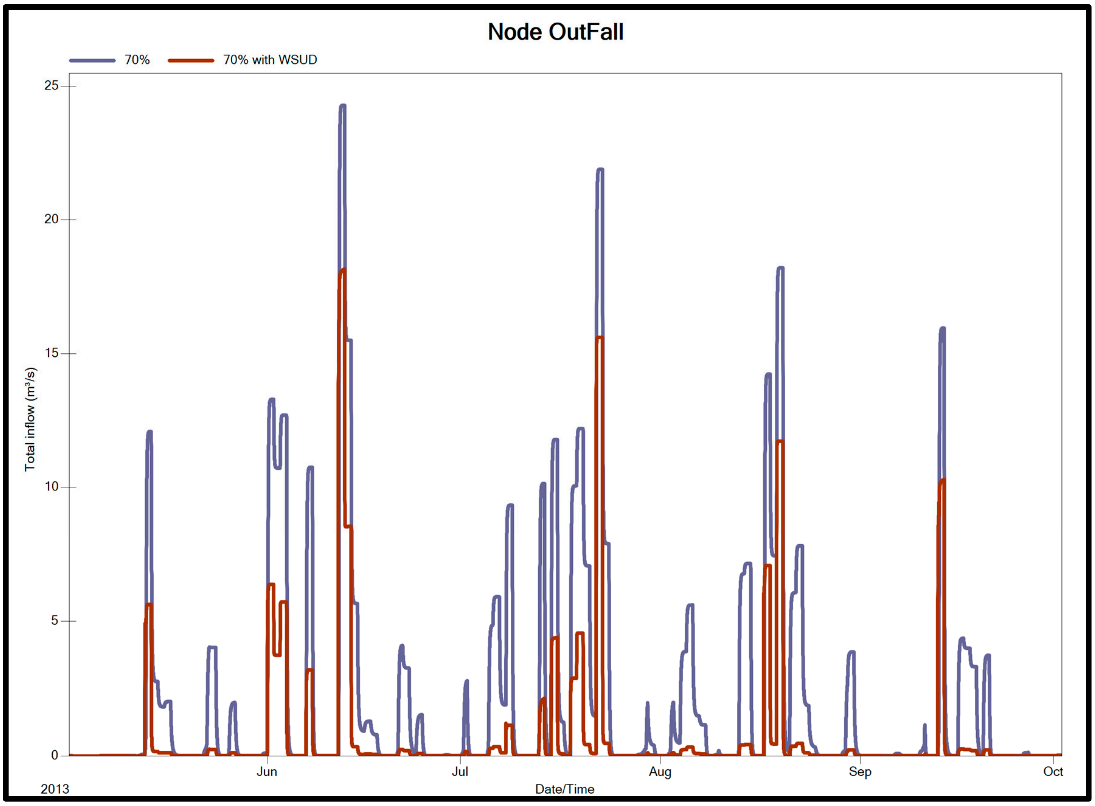

(**b**)

Figure 11. (**a**) Runoff comparison before and after Water Sensitive Urban Design (WSUD) for sub-catchment S1; (**b**) Runoff comparison before and after WSUD for the Myponga catchment outfall.

A comparison of floods at the catchment outfall as a result of the 70% urbanization scenario is presented in Figure 12. Bio-retention cells behaved differently for floods of different ARIs. It can be seen that bio-retention cells almost completely ameliorated 2-year ARI floods by reducing the frequency of such events from 44 to 2. Bio-retention cells worked well until the 20-year ARI. It is apparent that at larger ARIs (e.g., ARI = 50, 100 years), bio-retention cells were found to be ineffective at controlling flooding. Some reductions in peak flows were observed, however, that was not sufficient to control the event. The effectiveness of bio-retention cells as WSUD technologies for controlling floods has been supported by various past studies. For example, a field scale bio-retention garden effectively reduced both peak flow (70%) and runoff volume (42%) for a 180 mm, 24-h rainfall event [30]. Trowsdale and Simcock [31] constructed a bio-retention system that received water from a light industrial catchment and a busy road, and observed that the system was able to manage 55% of stormwater runoff from a rainfall event of 29 mm. Ermilio and Traver [32] also installed a bio-retention cell to capture a rainfall event of 25 mm and found it removed over 80% of the annual rainfall input to surface water. Li et al. [33] reported up to a 90% reduction in peak flow and an approximate two-hour delay of the peak. Hatt et al. [34] investigated the hydrologic performance of field scale bio-filtration systems; the findings showed that the systems were effective at attenuating peak runoff flow rates by at least 80%.

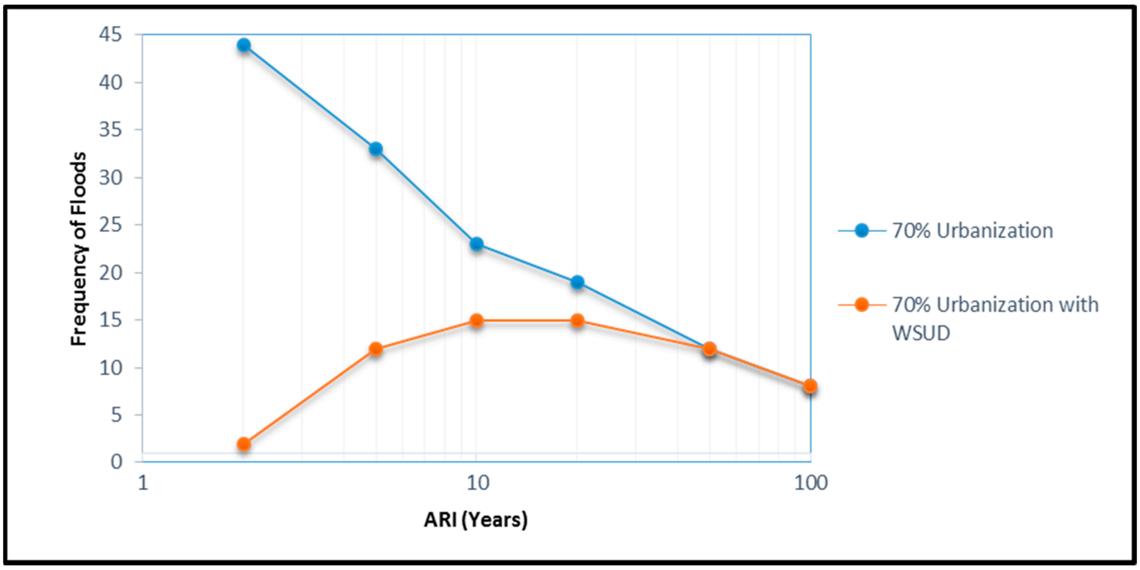

Figure 12. Flood frequencies at the catchment outfall with and without WSUD technology.

Whilst the results of this study show WSUD technology, i.e., bio-retention cells, to be highly effective for ameliorating frequent floods, caution needs to be exercised when considering the limitations and assumptions associated with the modelling. For example, the implementation of bio-retention cells requires specific soil properties, i.e., soil with less than 30% clay [35]. The Myponga catchment exhibits desirable conditions, having loamy and sandy soils across most of the catchment, however, this may not be the case for all catchments. Another crucial condition that needs to be considered is the geological strata below the subsoil. Generally, bio-retention cells require infiltrative geologic strata at or near the ground surface to accommodate infiltrated water. For the most part the Myponga catchment is characterised by suitable conditions, however, some parts of the Myponga also contain fractured rock aquifers, which are not suitable for infiltration. Consequently special techniques such as aquifer storage of infiltrated water (as recommended in Argue [35]) would be required.

4. Conclusions

In this paper the impacts of land use change on hydrological responses and the potential for using WSUD technologies to manage floods in urbanized catchments was examined. The investigation was performed using PCSWMM continuous simulation modelling of the Myponga catchment as a case study. The results of this investigation produced several important conclusions:

- An increasing trend in flow is larger than the increase in rainfall over the modelling period leading to strong effects of urbanization. This is demonstrated by a linear regression analysis of the historical data.
- Significant changes in hydrology, measured in terms of FDC, mean flow and FFC were evident when urbanization increased above the 10% level.
- As the percentage of urbanization increases, the frequency of flooding at varying ARIs also increased. The frequency of flood events at low ARIs (e.g., ARI 2, 5, 10, 20 years) increased more rapidly with increasing urbanization than at higher ARIs. This is indicative of low ARI floods being more sensitive to urbanization as compared to extreme floods at ARIs of 50–100 years.
- The implementation of bio-retention cells as suitable WSUD technologies is effective in reducing the frequency of small to medium floods (flood at ARI = 2, 5, 10 and 20 years).
- This work not only confirmed the general understanding that urbanization increases the risk of flooding and but also demonstrated the effectiveness of bio-retention cells as a suitable WSUD technology for alleviating floods and storm water management in the Myponga catchment.

This study provided findings that clearly demonstrate land use change impacts on hydrology, as well as endorsing current stormwater control policies which advocate the use of WSUD technologies. Such studies allow catchment planners/managers to evaluate the effectiveness of WSUD technologies in urbanized catchments.

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