



Assessing the Impact of Urban Development and On-Site Stormwater Detention on Regional Hydrology Using Monte Carlo Simulated Rainfall

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Abstract

Urban development is a contributor to increased peak runoff and adverse hydrologic effects in regional catchments. On-Site Stormwater Detention (OSD) is a common way to mitigate these problems, however it is well known that OSD can have the opposite effect when it is installed at inappropriate locations. Parameter uncertainty and the need for a probabilistic approach to hydrograph generation are also factors that add to concerns regarding our reliance on OSD for the protection of regional hydrology. This study contributes to awareness of these issues and a practical solution to the problem. A hydrologic model for Monte Carlo simulation of regional catchment hydrographs has been developed using interrelated modules based on previous studies. A sample of ten regional catchments has been modelled with three simulation scenarios: i) status quo, ii) a land parcel of varying sizes is urbanised at varying locations within the regional catchment, and iii) the urbanised land parcel includes OSD. The focus on the results has been the identification and analysis of two key parameters that influence the regional catchments' peak runoff, being the size and location of the urbanised land parcel. A regression analysis of the model results has revealed recurring patterns that have been used to develop new equations for predicting the mean impact of urbanisation and OSD on regional catchment peak runoff. The study highlights the significance of rainfall pattern uncertainty and the importance of considering land parcel location in considering the need for OSD as part of urban land development projects.

Keywords On-site Stormwater detention · Regional effect · Urban development · Runoff routing · Monte Carlo simulation

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1 Introduction

Increased imperviousness is the inevitable outcome of urbanisation. The impact is increased peak runoff and a variety of associated adverse effects on regional hydrology. Hollis (1975) showed that as a regional catchment reaches 30% imperviousness, the 100-year peak flow of runoff can double in comparison to those of their corresponding undeveloped catchments. Muñoz et al. (2018) showed that even as catchments that are already partially developed experience intensifying urbanisation, increasing peak flow of runoff will continue to rise. Increased peak runoff is known to lead to increased flooding issues, erosion, widening of channels, sediment deposition, increased pollutant delivery to streams, and other ecological disruptions (Arnold and Gibbons 1996; Booth 1991; Burns et al. 2012; Hood et al. 2007; Berland et al. 2017).

On-Site Stormwater Detention (OSD) is a well-established and effective solution to reduce peak runoff from a developed land parcel and act to mitigate the adverse impact of urbanization on regional hydrology (Bennett and Mays 1985). OSD works by collecting and temporarily storing runoff within a development site prior to its release to the downstream drainage network. The detained runoff is typically held in either underground tanks or above ground basins that allow for controlled outlet during and shortly after the storm event has finished.

The focus of OSD design is commonly the management of pre-development peak runoff at the outlet of an urbanized land parcel, which is often referred to as “micro-management” policy (Olenik 1999; Walesh 1989). McCuen (1974) provided some of the first evidence that this approach may accidentally increase flow rates in other parts of the regional catchment as a result of coincident hydrograph peaks at confluence locations. Early studies into solving this issue aimed to identify exclusion zones for OSD in the regional catchment, such as the lowest 20% (Bedient and Flores 1982) or the lowest one third (Leise 1991). More recent studies have focussed on the identification of optimal locations for OSD within the regional catchment that avoid the negative regional effect (Bellu et al. 2016; Duan et al. 2016; Kaini et al. 2007; Palmeri and Trepel 2002; Ravazzani et al. 2014; Shuster and Rhea 2013; Su et al. 2010; Tao et al. 2014; Travis and Mays 2008; Wang et al. 2017; Zhen et al. 2004). Unfortunately, the perfect land for OSD is not always available within the regional catchment due to a variety of town planning and land ownership issues. The skills and resources required to analyse regional catchments and specify OSD parameters are also not always available. These factors make micro-management style policies for OSD prevalent around the world (Fang et al. 2017; Pezzaniti et al. 2003; Schueler and Claytor 2000).

The successful design of OSD requires the ability to create and manipulate the shape of hydrographs to achieve the desired outflows. Many simple yet widely adopted methods for OSD design rely on idealised triangular or trapezoidal hydrographs (Abt and Grigg 1978; Donahue et al. 1981; Chow et al. 1988; Basha 1994; Boyd 1980; Carrol 1990; Hong et al. 2006; Hong 2008; Ronalds and Zhang 2017). The limitations of simplistic graphical methods are well known (Cordery 1971), and the more advanced and accurate method in common practice is to use hydrologic runoff routing models.

Temporal patterns of rainfall are key to the generation of hydrographs using runoff routing and in turn, the accurate design of OSD. However, like most hydrologic parameters they are not consistent or deterministic (Nathan et al. 2016). Future climate uncertainty is also expected to make recorded temporal patterns even less reliable for design purposes, with increased temporal pattern variability expected to occur in parallel with climate change (Mamo 2015; Fadhel et al. 2018). The development of probability-based methods such as Monte Carlo simulation have evolved to account for parameter uncertainties and take a probabilistic approach to hydrologic modelling. Monte Carlo simulation has been used for joint probability analyses of stream flow in Australian catchments by

Rahman et al. (2002), Nathan et al. (2003) and Babister et al. (2016a). Similar techniques have also been applied to catchments in Great Britain (Svensson et al. 2013) and Italy (Kottegoda et al. 2014). Monte Carlo simulation is an effective method of assessing precipitation uncertainty, and often used as a component of Bayesian flood forecasting to provide predictive distribution of flood events with uncertainty estimation (Han and Coulibaly 2017; Krzysztofowicz 1999).

This study differs to others by aiming to understand and quantify the impact on regional peak runoff that can be expected at a specific location downstream of an urbanised land parcel, considering development of that land parcel with, and without OSD. With Monte Carlo simulation adopted to account for temporal pattern uncertainty, the aim is to provide a simplistic, universally applicable method to estimate the mean impact on peak regional catchment runoff.

2 Materials and Methods

An integrated hydrologic model has been developed to perform runoff routing of probability-based rainfall temporal patterns and generate hydrographs of regional catchment runoff. The methodology has focussed on extracting and comparing the peak runoff results for three key scenarios:

- 1) the existing status quo;
- 2) a land parcel within the regional catchment is urbanised (without OSD); and
- 3) the urbanised land parcel includes OSD.

The hypothetical location of the land parcel within the regional catchment and the area of the land parcel were both varied under controlled conditions for each scenario.

The model was calibrated using flood frequency analysis outputs and used to simulate a sample of ten actual regional catchments of varying sizes and locations. The response of the regional catchments' peak flow results to variation in the land parcel's location and size parameters were analysed to identify recurring and predictable patterns. A regression analysis on the results was finally used to develop a system of equations for predicting the mean impact of urbanisation and OSD on the regional catchment peak flow.

The model, as described by the flow chart in Fig. 1, incorporates Monte Carlo simulation for the generation of random temporal patterns (1000 patterns for each scenario), a loss model to account for catchment infiltration, non-linear catchment routing, Muskingham stream routing, and level pool routing of OSD.

2.1 Monte Carlo Temporal Pattern Simulation

Monte Carlo simulation of random temporal patterns was adopted using the Multiplicative Cascade Model as described by Olsson (1998). An initial rainfall depth, R , over a period of T , was distributed between time steps in a time series using the weights $W_{i,1}$ and $W_{i,2}$ to disaggregate the rainfall, where i is the cascade level:

$$W_{i,1}, W_{i,2} = \begin{cases} 0 & \text{for } P(0/1) \\ 1 & \text{for } P(1/0) \\ x & \text{for } P(x/(1-x)), 0 < x < 1 \end{cases} \quad \begin{matrix} W_{i,1} = x_i \\ W_{i,2} = 1 - W_{i,1} \end{matrix} \quad (1)$$

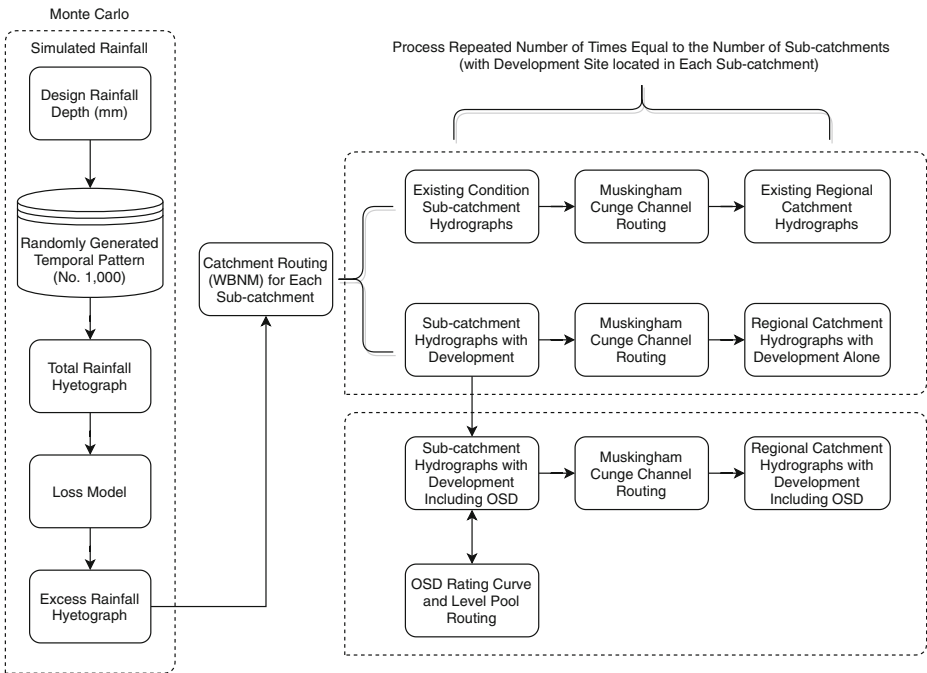


Fig. 1 Model development flow chart

P is the probability of the rainfall amount in a time step branching from one position in the starting cascade to a split between two positions in the next cascade, where $P(0/1)$, $P(1/0)$ and $P(x/(1-x))$ are the probabilities of no rainfall, all of the rainfall, and a distribution of $x/(1-x)$ respectively. The random variable $0 \leq x \leq 1$ is used to disaggregate the rainfall from a single value in the starting cascade to the two random values in the next cascade. The volume of rainfall in the storm event remains the same with each cascade as the number of points in the time series doubles and the rainfall is disaggregated throughout the time series. Once reaching a satisfactory number of cascades to provide a suitable time step resolution $\Delta t = \frac{T}{2^n}$, the process was complete and an artificial rainfall temporal pattern was generated. A suitable time step resolution results in a realistic generation of hydrograph shape that avoids numerical instability in the modelling and without excessive computation. The modelling agreed with a study of 24 catchments in Northern Germany by Müller and Haberlandt (2018), revealing optimal accuracy when the disaggregation process resulted in $\Delta t = 5$ to 7.5 minutes duration time steps.

2.2 Regional Catchment Conceptualisation and Routing Model

The regional catchment model was conceptualised using a combination of catchment and stream flow routing, with the regional catchments divided into ten equal area sub-catchments. Runoff from each sub-catchment was routed to its outlet and combined with the upstream hydrograph for stream flow routing to the downstream sub-catchment. Multiple sizes of hypothetical land parcels within the regional catchment were modelled with areas of 1, 2, 5, 10, 20, 50 and 100 ha.

Rainfall from each of the randomly generated temporal patterns was adjusted before routing to account for losses. The Initial Loss - Continuing Loss (IL/CL) model was adopted for this

study in accordance with Hill and Thompson (2016), where:

$$Loss = \begin{cases} Rain < \text{for } 0 < Rain < IL \\ CL < \text{for } Rain > IL \end{cases} \tag{2}$$

For the conversion of rainfall excess to runoff from the sub-catchments the continuity equation was utilised, where the catchment outflow (Q) is related to the catchment inflow (I) and storage (S) at each time step:

$$\frac{dS}{dt} = I(t) - Q(t) \tag{3}$$

$$S = kQ^m \tag{4}$$

The solution to the coefficient k developed by Boyd et al. (1993) and utilized in the runoff-routing software WBNM was adopted as per Eqs. (5) and (6) for pervious and impervious portions of the catchment area (A) respectively. The non-linearity parameter m was taken as 0.77, which has been demonstrated to be the most appropriate for potentially saturated conditions (Rezaei-Sadr et al. 2012). The C_{lag} coefficient is a dimensionless parameter that is used to calibrate the equations, with values between 0.5 and 2.0 adopted for each catchment and validated using gauged flood frequency analysis results.

$$k_{pervious} = (C_{lag} A^{0.57} Q^{-0.23}) Q^{1-m} \tag{5}$$

$$k_{impervious} = (0.1 C_{lag} A^{0.25}) Q^{1-m} \tag{6}$$

For the routing of streamflow between the confluence of each sub-catchment the Muskingham routing procedures were adopted in accordance with Nash (1959):

$$Q_{n+1} = C_1 I_{n+1} + C_2 I_n + C_3 Q_n \tag{7}$$

Where:

$$C_1 = 1 - \frac{K(1-c)}{\Delta t} \tag{8}$$

$$C_2 = 1 - \frac{K(1-c)}{\Delta t} - c \tag{9}$$

$$C_3 = c \tag{10}$$

$$c = \frac{-\Delta t}{e^{K(1-X)}} \tag{11}$$

The value of X is a physical parameter that reflects the flood peak attenuation and hydrograph shape flattening of a diffusion wave in motion. A constant value of 0.4 was adopted for all the catchments used in this study, in accordance with the recommendations of Xiaofang et al. (2008). The value for K is a variable dependent upon the catchment imperviousness (Imp) and area (A) which was modelled in accordance with Boyd et al. (1987):

$$K = 3600(1 + Imp)^{1.9} \cdot 1.3(A)^{0.38} \tag{12}$$

Figure 2 provides a conceptualisation of the model set-up.

2.3 Detention Routing

The effect of the OSD was modelled using level pool routing. To describe the outflow of the OSD at various storage depths during the simulation (Q_h), a rating curve was developed in accordance with Ronalds and Zhang (2017):

$$Q_h = \begin{cases} \frac{1}{n} A_w \left(\frac{A_w}{P} \right)^{\frac{2}{3}} S_g^{\frac{1}{2}} + C_w L_w h_{weir}^{\frac{3}{2}} & \langle \text{for } h \leq D \rangle \\ A_p \sqrt{\frac{2gD(h-h_{DS})}{L f_D}} + C_w L_w h_{weir}^{\frac{3}{2}} & \langle \text{for } h > D \rangle \end{cases} \tag{13}$$

The parameters A_w , P , D , L , n and S_g are the outflow pipe area, wetted perimeter, diameter, length, roughness and gradient respectively. The parameters C_w , L_w and h_{weir} are the weir coefficient, length and height of flow respectively. The depth of water in the tank is h and the standing water level downstream of the tank is h_{DS} .

The Darcy–Weisbach friction factor, f_D , is described by Eq. (14) (Brown 2002), which is dependent upon the Reynolds number, Re .

$$\frac{1}{\sqrt{f_D}} = -2 \log \left(\frac{5.76}{Re^{0.9}} \right) \tag{14}$$

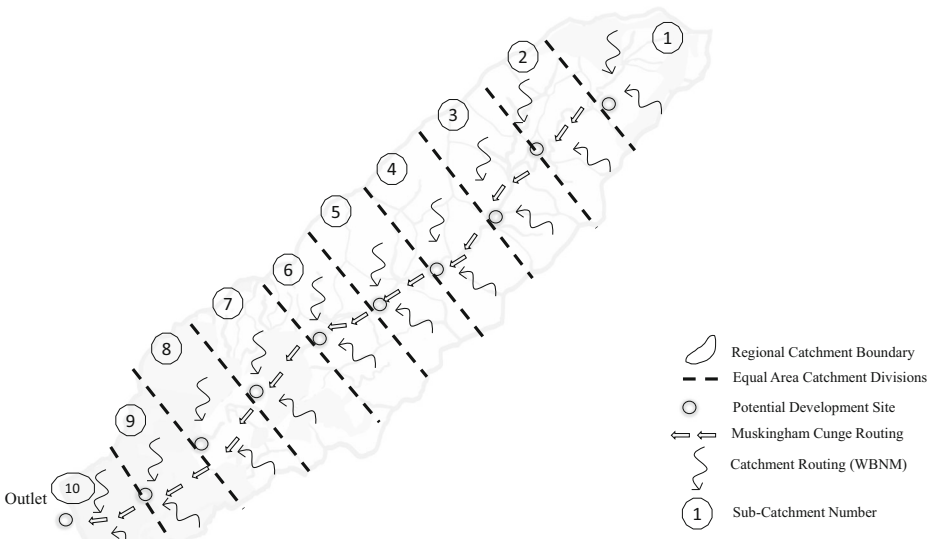


Fig. 2 Regional catchment conceptualisation model

2.4 Sample Regional Catchment Details

A sample of ten regional catchments was used for modelling, with their locations shown in Fig. 3. All are located along the eastern coastline of Australia and within local government areas that mandate the usage of OSD. Care was taken to select catchments that include partial urbanisation without significant major on-line storage systems like water storage reservoirs. The sizes of the catchments vary from 3000 to 213,000 ha and the imperviousness ranges from 10 to 25%, as measured via aerial photography.

Rainfall depths and durations were obtained from Intensity-Frequency-Duration data for each specific catchment, relating to a 1% Annual Exceedance Probability (AEP) event. The flood level resulting from the critical 1% AEP flood event is the mandated prescriptive for exclusion of development and enforcement of development controls throughout Australia (Cook 2017). All rainfall depth and IL/CL parameters were taken from the Australian Rainfall and Runoff data hub (Babister et al. 2016b) and summarised in Table 1.

The effect of urbanisation on the hypothetical land parcels was modelled as an increase of imperviousness to 90%. The volume of each OSD was modelled as 300m³/ha, which was determined from experimentation to be an effective size for reducing post-development peak

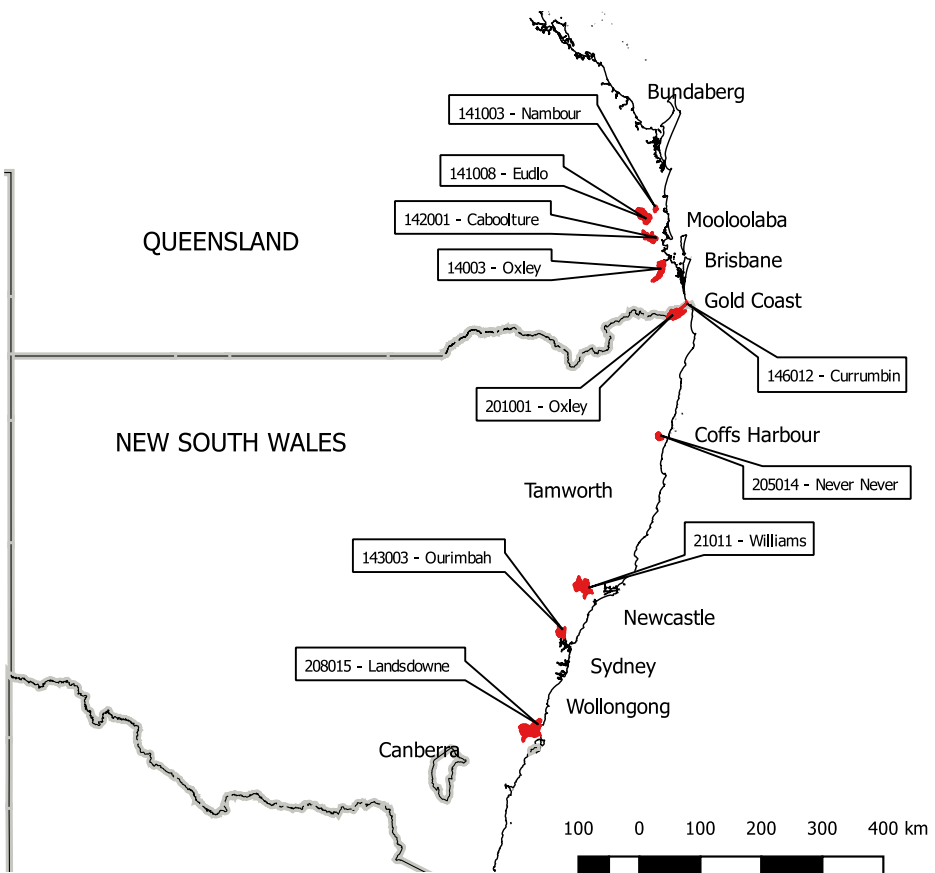


Fig. 3 Locations of regional catchments

Table 1 Detailed hydrologic parameters from the sample of regional catchments

Bureau of meteorology ID	Regional catchment name	Area (ha)	Impervious (%)	6 h rainfall depth (mm)	12 h rainfall depth (mm)	24 h rainfall depth (mm)	Losses (mm)
146,012	Curumbin QLD	3000	12	290	415	565	IL = 43, CL = 3.4
142,001	Caboolture QLD	9400	18	248	334	447	IL = 43, CL = 3.4
201,001	Oxley NSW	21,300	15	276	403	557	IL = 20, CL = 2.3
205,014	Never Never NSW	5100	10	238	359	523	IL = 45, CL = 4.1
208,015	Landsdowne NSW	9600	17	176	237	324	IL = 42, CL = 5.3
141,003	Nambour QLD	3800	20	255	376	544	IL = 40, CL = 2.4
141,008	Eudlo QLD	6200	10	256	371	533	IL = 25, CL = 2.5
210,011	Williams NSW	19,400	22	178	249	349	IL = 33, CL = 4.2
143,003	Oxley QLD	6000	25	157	205	277	IL = 24, CL = 1.6
143,003	Ourimbah NSW	8300	25	173	227	304	IL = 58, CL = 3.5

discharge to pre-development conditions. The OSD volume is also commensurate with the policies of Council's that adopt site storage requirements that target pre-development flow rate conditions, such as Brisbane (Brisbane City Council 2014), Kogarah (Singh et al. 2007), Wollongong (Silveri and Rigby 2006) and various others in the Greater Sydney region (Phillips and Yu 2015).

From each simulation of 1000 random temporal patterns, the effectiveness of OSD in achieving pre-development peak runoff at the development site outlet was found to be in the order of 30–60%. This outcome is commensurate with the expected performance of real-world OSD systems that have been design using event-based techniques (Ronalds et al. 2017).

2.5 Verification of Model Setup

Each regional catchment used for modelling is gauged, with flood frequency analysis results available from the Australian Rainfall and Runoff Regional Flood Frequency Estimation Model (RFFEM) (Rahman et al. 2015a, b). The accuracy of the Monte Carlo simulation has been verified by comparing the model results to the outputs of the RFFEM. In Table 2, the mean (μ), lower confidence limit ($\mu - 2\delta$) and upper confidence limit ($\mu + 2\delta$) from the Monte Carlo model results are shown in comparison to the mean and 95% confidence limits published by the RFFEM.

3 Results and Discussions

For all the regional catchments modelled in this study, recurring patterns for the impact of development and OSD on regional catchment peak runoff were observed.

The factor of impact to peak runoff as a result of development alone (F_{dev}) was found to be an increase when the land parcel is in the upper portions of the catchment. As the land parcel gets nearer to the outlet of the catchment F_{dev} is reduced to negative, indicating decreased runoff close to the catchment outlet. The factor of impact on regional outflow because of OSD (F_{det}) was found to follow an inverse relationship to F_{dev} , resulting in decreases to regional outflow when the land parcel is located in the upper portions of the catchment and an increased F_{det} at the lower portions of the catchment. Figure 4 diagrammatically shows the recurring

Table 2 Verification of Monte Carlo model to RFFEM outputs (1% AEP)

Catchment	Monte Carlo results (m ³ /s)			RFFEM results (m ³ /s)		
	$\mu + 2\delta$	μ	$\mu + 2\delta$	Lower 95% confidence	Peak flow	Upper 95% confidence
Currumbin QLD	168.1	376.7	585.4	278.2	371.4	582.0
Caboolture QLD	514.8	1098.6	1682.5	756.7	1107.7	2145.2
Oxley NSW	953.8	1900.5	2847.2	1444.2	1906.6	2937.7
Landsdowne NSW	289.1	679.2	1069.3	467.49	684.44	1368
Never Never NSW	194.4	359.6	524.9	253.79	308.7	476.3
Nambour QLD	297.8	539.3	780.8	342	530.4	1037.1
Eudlo QLD ^a	375.2	605.8	836.4	348	608.92	1548.5
Williams NSW	787.4	1600.1	2412.8	1188.9	1624.76	2583.7
Oxley QLD	172.3	414.1	655.9	299.32	397.87	1177.2
Ourimbah NSW	228.9	522.2	815.4	246.3	508.9	1689.9

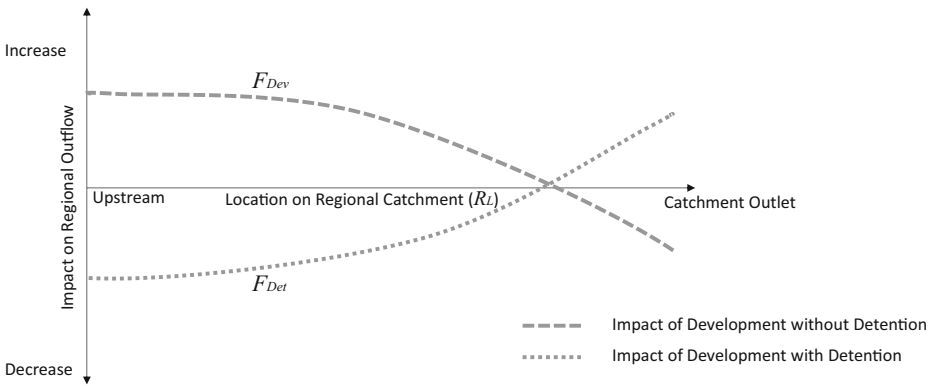


Fig. 4 Diagrammatic of observed response to regional catchment peak flow for development with and without OSD at varying land parcel locations

trendlines of F_{dev} and F_{det} that were observed with respect to land parcel location within the regional catchment.

3.1 Factor of Impact Resulting from Development (F_{dev})

Figure 4 shows a second order polynomial trend that repeatedly occurred during the assessment of the regional catchments investigated in this study. The general form of F_{dev} is provided in Eq. (15), where R_L identifies the land parcels location in the regional catchment based on the distance of the site from the regional catchment outlet (L_{site}) and the total regional catchments flow path length ($L_{regional}$).

$$F_{dev} = aR_L^2 + bR_L + c \tag{15}$$

$$R_L = \frac{L_{site}}{L_{regional}} \tag{16}$$

The coefficients a , b and c were found to vary in a linear relationship with respect to the ratio of the development size to the regional catchment size (R_C). Table 3 shows the linear gradients

Table 3 Linear relationship of F_{dev} polynomial coefficients to R_C

Catchment	a		b		c	
	Linear gradient	R ²	Linear gradient	R ²	Linear gradient	R ²
Curumbin QLD	-0.178	0.956	-0.150	0.997	0.240	0.996
Caboolture QLD	-0.091	0.996	-0.100	0.920	0.157	0.994
Oxley NSW	-0.093	0.998	-0.114	0.980	0.168	0.995
Landsdowne NSW	-0.075	0.973	-0.196	0.999	0.332	0.999
Never Never NSW	-0.141	0.944	-0.132	0.914	0.300	0.944
Nambour QLD	-0.025	0.983	-0.028	0.946	0.104	0.986
Eudlo QLD	-0.173	0.986	-0.090	0.820	0.215	0.989
Williams NSW	-0.017	0.677	-0.135	0.972	0.187	0.998
Oxley QLD	-0.168	0.996	-0.072	0.986	0.206	0.995
Ourimbah NSW	-0.136	0.990	-0.073	0.974	0.258	0.998

of a , b , and c with respect to R_C , as well as the coefficient of determination (R^2), indicating the strength of linearity.

To establish a universal solution applicable to catchments that are not included in the study, Fig. 5 below provides the results of curve fitting exercises for each coefficient, considering all data points generated by the study.

Based on the regression analysis of coefficients a , b and c to with respect to R_C , the empirical equation form for each coefficient is defined as follows:

$$a = -0.1R_C \quad (17)$$

$$b = -0.1R_C \quad (18)$$

$$c = 0.15R_C \quad (19)$$

Combining Eq. (15) with the linear forms of a , b and c yields Eq. (20), where F_{dev} is a function of R_C and R_L :

$$F_{dev} = R_C [-0.1R_L^2 - 0.1R_L + 0.15] \quad (20)$$

3.2 Factor of Impact Resulting from Development with OSD (F_{det})

The general form of F_{det} is provided in Eq. (21), which was observed to follow an inverse relationship to F_{dev} as shown in Fig. 4.

$$F_{det} = iR_L^2 + jR_L + k \quad (21)$$

The coefficients i , j and k were also found to vary with a linear relationship respecting R_C for each regional catchment. Table 4 shows the results for each catchment individually and Fig. 6 shows the results of the curve fitting exercises for each coefficient considering all data points generated by the study.

Based on the regression analysis of coefficients i , j and k to with respect to R_C , the empirical equation form for each coefficient is defined as follows:

$$i = 0.3R_C \quad (22)$$

$$j = -0.15R_C \quad (23)$$

$$k = -0.1R_C \quad (24)$$

Combining Eq. (21) with the linear forms of i , j and k yields Eq. (25), where F_{det} is a function of R_C and R_L :

$$F_{det} = R_C [0.3R_L^2 - 0.15R_L - 0.1] \quad (25)$$

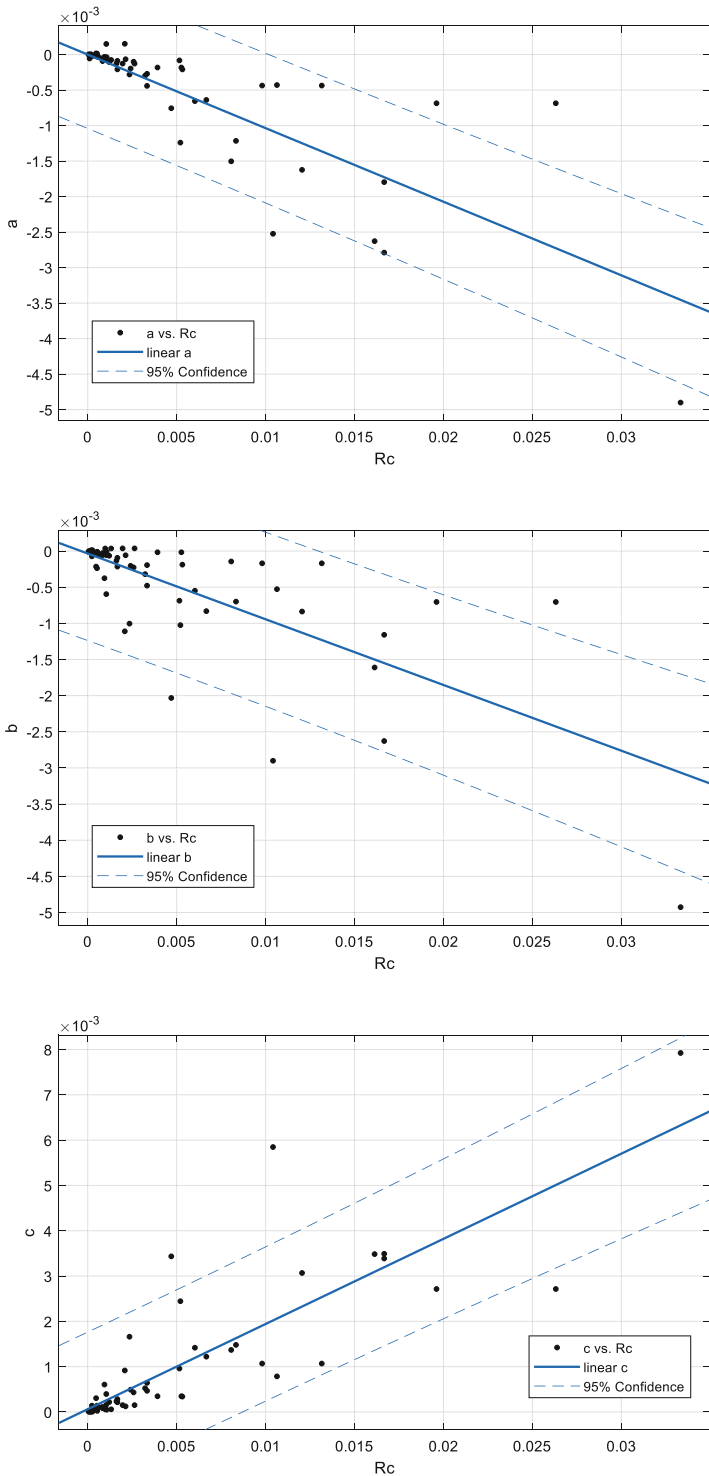


Fig. 5 Linear regression of coefficients a , b and c with respect to R_C

Table 4 Linear relationship of F_{det} polynomial coefficients to R_C

Catchment	<i>i</i>		<i>j</i>		<i>k</i>	
	Linear gradient	R ²	Linear gradient	R ²	Linear gradient	R ²
Currumbin QLD	0.408	0.999	-0.248	0.972	-0.081	0.884
Caboolture QLD	0.439	0.999	-0.237	0.986	-0.155	0.982
Oxley NSW	0.177	0.996	-0.066	0.938	-0.019	0.413
Landsdowne NSW	0.453	0.980	-0.377	0.977	0.091	0.991
Never Never NSW	0.292	0.974	-0.272	0.985	0.112	0.960
Nambour QLD'	0.066	0.998	-0.080	0.249	-0.168	0.982
Eudlo QLD'	0.172	0.995	-0.034	0.883	-0.024	0.596
Williams NSW	0.413	0.977	-0.245	0.955	0.080	0.920
Oxley QLD	0.226	0.964	-0.156	0.878	-0.106	0.108
Ourimbah NSW	0.267	0.964	-0.210	0.954	0.018	0.416

Equations (20) and (25) are the key findings of this study that may be used in future applications to predict the mean impact on regional peak runoff that is the result of urbanisation alone, and with OSD respectively.

4 Verification and Example Case Study - Tallebudgera Creek Catchment

The Tallebudgera Creek catchment outlets to the Pacific Ocean via a narrow river mouth at Burleigh Heads on the Gold Coast, Queensland, Australia. Most of the recent urbanisation is in the lower portions of the catchment surrounding the primary streamline, with rapidly expanding and intensifying beachside and estuarine suburbs including Burleigh Waters and Elenora located in the lower portions of the catchment area. At the river gauging station located in the lower, urbanised portion of the catchment (BoM ID: 146007) the upstream catchment area is 5700 ha. Figure 7 provides a diagrammatic of the catchments shape, land use and gauging station location.

This example of a typical regional catchment has been used to demonstrate the recurring patterns observed through all ten of the sample catchments, and to demonstrate the ability of Eqs. (20) and (25) to predict F_{dev} and F_{det} .

To validate the accuracy of the base case model used for simulation of the Tallebudgera Creek, the Monte Carlo simulation results for 1000 temporal patterns modelling the 1% AEP rainfall event in the existing case scenario are shown in Fig. 8. The full spread of hydrograph results are shown, with the mean identified in solid linework. The mean peak runoff from the Monte Carlo modelling is calculated as 731.7m³/s, which compares well to the RFFEM outputs of 732.3m³/s.

A 10 ha urban land parcel has been hypothesised. This would be representative of a 50–100 lot townhouse project or a large commercial development with associated roadworks and carparks creating impervious surfaces.

The full results of the Monte Carlo simulation are presented in Fig. 9. A grey line is presented for each model simulation, showing the percentage of impact on regional catchment peak flow that results from development with, and without OSD at incremental locations within the catchment. The horizontal axis represents the location of the development site within the regional catchment, with the outlet on the right-hand-side. 1000 grey lines are shown for the scenario of development alone and 1000 grey lines are shown for the scenario of

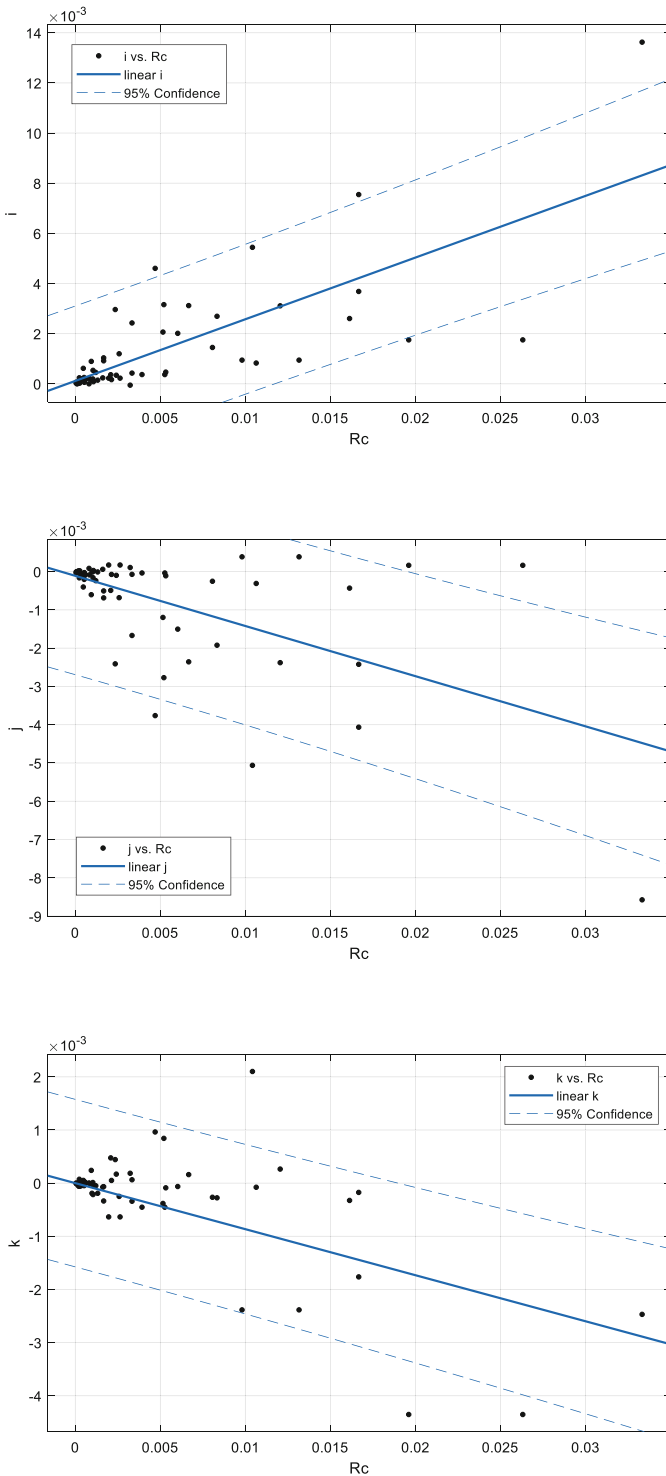


Fig. 6 Linear Regression of Coefficients i, j and k with Respect to R_C

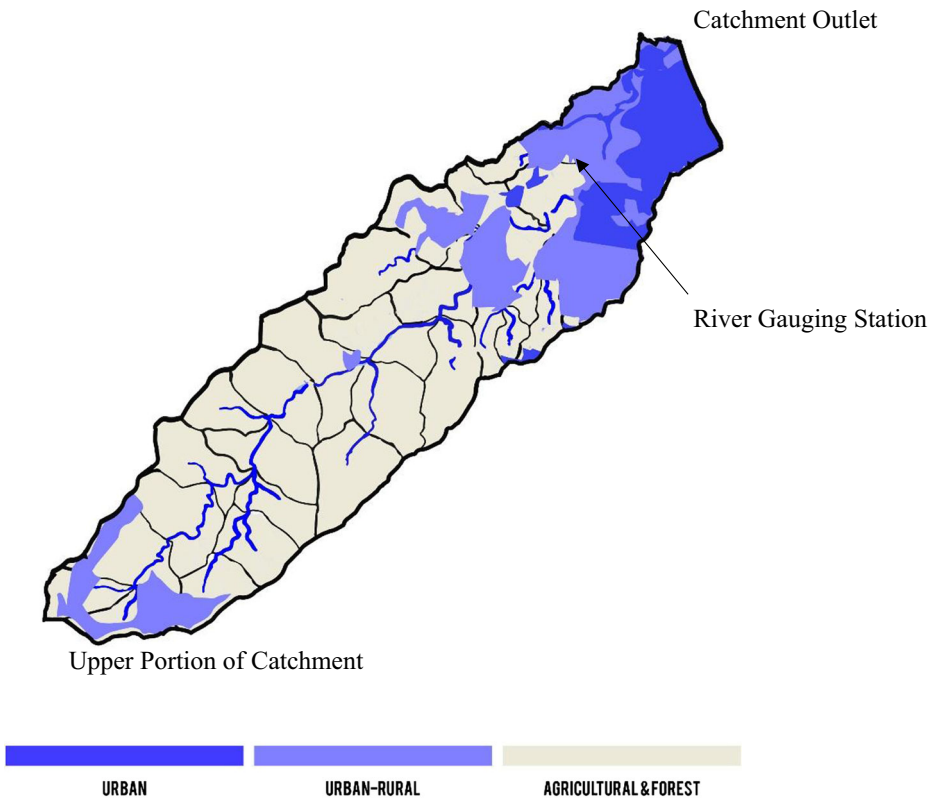


Fig. 7 Tallebudgera Creek catchment land usage

development with OSD. A dashed line is shown to represent the mean of the Monte Carlo simulation results for each scenario.

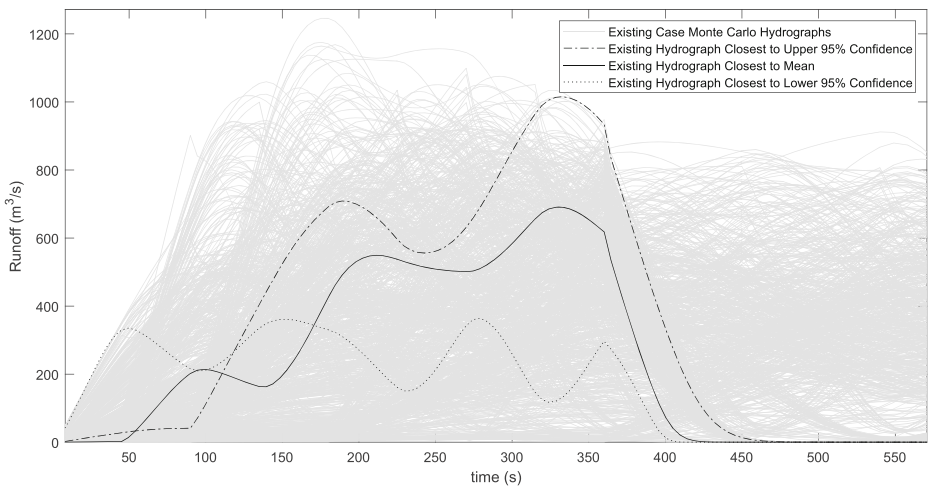


Fig. 8 Tallebudgera Creek Monte Carlo simulation of regional catchment hydrographs

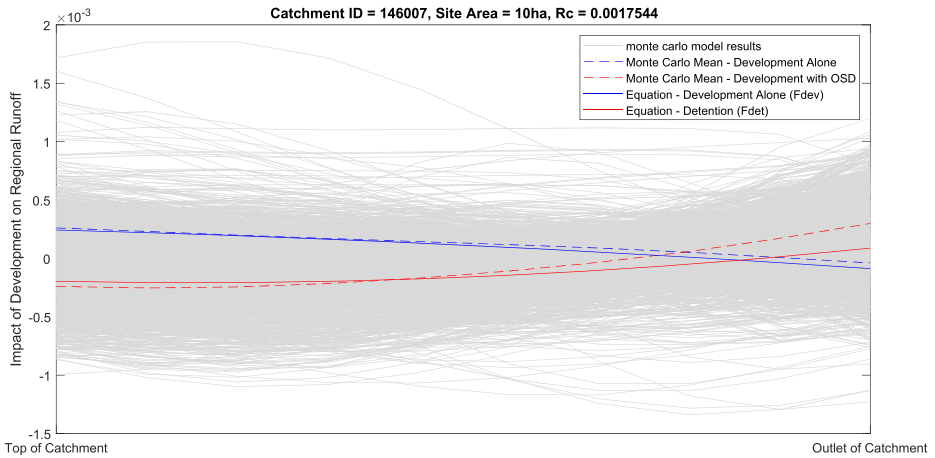


Fig. 9 Monte Carlo & Equation Results for Development Impacts in the Tallebudgera Creek Catchment

The calculated prediction of the mean impacts using Eqs. (20) and (25) are also shown in solid lines. The calculated F_{dev} and F_{det} from the equations are shown to achieve a close fit to the mean of the Monte Carlo model results, even though this catchment was not considered in the regression or determination of the equations.

4.1 Specific Test Location Analysis

Two specific locations of land parcels have been focussed upon for detailed analysis of the model results, one in the upper 20% of the catchment ($R_L = 0.8$) and another in the lowest 10% of the catchment ($R_L = 0.1$). Table 6 summarises a comparison of the results from using Eqs. 20 and 25 for predicting F_{dev} and F_{det} respectively against the Monte Carlo model results at each location.

The results in Table 6 show a validation of equations by comparison to the mean results of the Monte Carlo simulations.

Further review of the simulation results was undertaken to assess the number of occurrences of increases or decreases to the regional catchment peak flow. In the upper portion of the catchment, 990 of the 1000 F_{dev} simulations showed an increase in regional catchment peak

Table 6 Comparison of calculated impact of development (F_{dev}) to Monte Carlo results

	Upper catchment		Lower catchment	
	% impact	m ³ /s impact	% impact	m ³ /s impact
Calculated F_{dev} from Eq. 20	+0.022	+0.161	-0.004	-0.027
Mean Monte Carlo F_{dev} (μ)	+0.023	+0.168	-0.004	-0.027
Upper confidence Monte Carlo F_{dev} ($\mu + \delta$)	+0.041	+0.300	+0.020	+0.150
Lower confidence Monte Carlo F_{dev} ($\mu - \delta$)	+0.005	+0.037	-0.020	-0.150
Calculated F_{det} from Eq. 25	-0.021	-0.154	+0.002	+0.015
Mean Monte Carlo F_{det} (μ)	-0.022	-0.161	+0.005	+0.037
Upper confidence Monte Carlo F_{det} ($\mu + \delta$)	-0.039	-0.285	+0.022	+0.161
Lower confidence Monte Carlo F_{det} ($\mu - \delta$)	-0.005	-0.037	-0.010	-0.073

runoff resulting from urbanisation of the land parcel. When OSD was modelled however, the F_{det} results reduced to only 71 of the 1000 simulations. In the lower portion of the catchment, 576 of the 1000 F_{dev} simulations showed an increase in regional catchment peak runoff, which was increased to 718 of the 1000 when OSD was modelled.

5 Conclusions

A model was developed for Monte Carlo simulation of 1000 randomly generated temporal patterns on ten regional catchments with seven differing land parcel sizes located throughout each catchment. A summary of the findings is as follows:

- Monte Carlo simulation of temporal patterns with design rainfall depth and duration has been shown to generate comparable results to regional flood frequency analysis for the mean and 95% confidence limits of peak flow magnitude;
- Under the dominating influence of temporal pattern uncertainty, peak runoff from all of the regional catchments modelled in this study behaved similarly in response to urbanisation and OSD at varying locations in the regional catchment;
- The mean impact of urbanisation (F_{dev}) and urbanisation with OSD (F_{det}) on regional catchment peak runoff were both found to be dependent upon the location of the land parcel (R_L) and the ratio of land parcel to regional catchment area (R_C).
- A regression analysis of the model results was used to develop equations for the prediction of F_{dev} and F_{det} . The equations have been tested and verified using an eleventh regional catchment.
- The study has shown that OSD can reduce a 99% chance of increased runoff to less than 8% when a land parcel is in the upper reaches of a catchment. In the lower portions of the same catchment however, the same OSD has a 72% change of increasing runoff, compared to a 58% chance without.
- This study has highlighted the importance of considering land parcel location in the determination of need for OSD as part of urban land development projects.
- This study has highlighted temporal pattern uncertainty as a major concern for the design of, and reliance on OSD for the protection of regional catchment hydrology.

Compliance with Ethical Standards

Conflict of Interest None.

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