Sensitivity Analysis of Developed Hydrologic, Hydraulic and Stormwater Quality Model

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Abstract

Sensitivity analysis of model parameters is the most effective way of evaluating the performances of complex hydrologic, hydraulic and stormwater quality models. The key objectives of sensitivity analysis is to identify important parameters that are most sensitive to model outputs and further plays an important role in parameterization, calibration, validation, optimization and uncertainty assessments. In this study sensitivity analysis was performed on seven calibration parameters including initial loss (IL), time of concentration (TC), reduction factor (RF), time-lag (TL), build-up rate (a), time exponent (b) and wash-off coefficient (k) of developed hydrologic, hydraulic and stormwater quality model in R software. The analysis results noted that for peak flow, total runoff volume and mean flow estimations, reduction factor is the most sensitive parameter whilst for total suspended solid (TSS) load estimation, build-up rate is the most sensitive parameters. The approach adopted in this study will help to assessing sensitive parameters enabling effective calibration of hydrologic, hydraulic and stormwater quality models and increase the accuracy in estimation of stormwater quantity and quality for urban stormwater management and hydraulic structure design.

Keywords: *Sensitivity analysis, Hydrologic model, Hydraulic model, Stormwater quality model, R software.*

1 Introduction

Accurate stormwater quality modelling outcomes is essential for effective stormwater treatment system design (Francey et al., 2010). Stormwater quality model is primarily consists of a hydrologic-hydraulic model (rainfall-runoff model) and water quality model (pollutant processes model). Hydrologic-hydraulic model is typically used to simulate stormwater quantity. In water quantity simulation, hydrologic-hydraulic model simulates processes such as runoff generation (conversion of rainfall into surface runoff), runoff routing (translation of surface runoff into the catchment outlet) and conveyance of flow in pipes and channels (Zoppou, 2001). The water quality model simulates stormwater pollutant processes such as build-up and wash-off (Singh & Woolhiser, 2002; Zoppou, 2001). Pollutant built-up is the process which explains the accumulation of pollutants on impervious surfaces during dry weather conditions (Vaze and Chiew, 2002), and pollutant wash-off refers to slackening and detachment of accumulated pollutants (build-up) from impervious surfaces during rainfall events (Brodie and Rosewell, 2007).

Outcomes of stormwater quality model is used for diverse applications including stormwater treatment designs, urban land use management and water sensitive urban design (Song et al., 2015). Due to its widespread applications, approaches to increase the reliability of model outcomes by developing parameter evaluation techniques such as sensitivity analysis, optimization and uncertainty assessment are essential. It is commonly known that the reliability of stormwater quality modelling outcomes depends on the accuracy of model structure, reliability of input data, significance of input parameters and boundary conditions (Dotto et al., 2009; Foglia et al., 2013). Loosvelt et al. (2013) noted that the knowledge of significance and sensitivity of input parameters to final outcomes can increase the reliability of decision making. In this regard, sensitivity analysis is one of the effective tools used for identifying most sensitive parameters in stormwater quality modelling.

Stormwater quality models are simplified representations of hydrologic-hydraulic and stormwater pollutant processes. Processes models in the form of mathematical equations are used to replicate these processes and contain a range of different parameters, which have direct relation with catchment and pollutant characteristics.

Van Griensven et al. (2006) noted that the use of insignificant parameters or over parameterization of models can lead to the calibration issues. Hence identification of significant and sensitive parameters using efficient analysis is essential in modelling practices. A range of sensitivity analysis methods are commonly in use (Frey and Patil, 2002; Saltelli et al., 2012; Hamby, 1994). This includes global, local, mathematical, statistical, screening, graphical, qualitative, refined and quantitative methods. These methods vary widely in terms of their formulation, application, algorithm structure and parameter evaluation aspects (Song et al., 2015). Hence the modeller should choose a suitable method so that it can fit the developed model well and interpret the significant model parameters in connection to model outputs (White and Chaubey, 2005).

This study aims to perform sensitivity analysis for a stormwater quality model to identify the most sensitive parameters to model outputs. To achieve this aim, a stormwater quality model was programmed in R software using widely used hydrologic, hydraulic and pollutant processes models. The sensitivity analysis was performed for model parameters based on relative sensitivity measures. Evaluation of sensitivity measures were done in relation to multiple output forms including peak flow, mean flow, total runoff volume and pollutant load (White and Chaubey, 2005). This enabled identification of the influence of catchment and pollutant characteristics on sensitivity of developed model parameters so that the accuracy in model outcomes is ensured.

2 Materials and Methods

2.1 Study Location

Study sites were selected from Gold Coast region, South East Queensland, Australia. Three catchments were selected so that they have different catchment area, impervious fraction and urban form. This will enable to understand the influence of different catchment characteristic on sensitivity of parameters. Selected catchments were namely Alextown, Gumbeel and Birdlife Park, located within the Highland Park residential area as shown in Figure 1. These three catchments had been monitored for local rainfall, runoff and stormwater quality. The required catchment data were obtained from the review of previous research study conducted by Egodawatta et al. (2009) and drainage system network data were collected from Gold Coast City Council (GCCC) data bases.

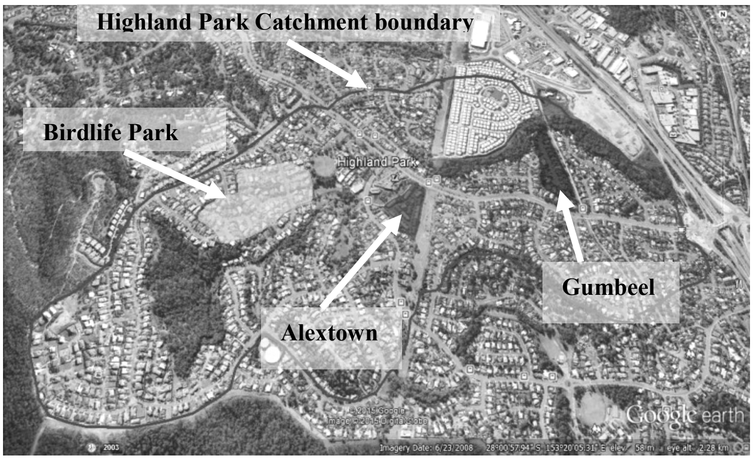

Figure 1. Location of study catchments

2.2 Selection of Hydrologic, Hydraulic and Stormwater Quality Model

Time-area routing method is selected as hydrologic model due to its widespread use in commercial modelling software such as MIKE URBAN (MOUSE), ILSAX and DRAINS (Urban, 2012; Zoppou, 2001). In addition time-area method requires only a few parameters for physical interpretation of the catchment (Urban, 2012). Due to this, the time-area routing model requires less computational effort compared to other physically and conceptually based models. Similarly, time-lag method was selected to develop hydraulic model. Time-lag method calculates the maximum travel time for runoff through pipe or channel network (USDA, 2010). Pollutant process models for pollutant build-up and wash-off were selected and used in formulated model. The equations adopted have been successfully used in previous research studies (Ball et al., 1998; Egodawatta et al., 2013).

2.3 Development of Hydrologic, Hydraulic and Stormwater Quality Model

Selected hydrologic, hydraulic and stormwater quality models were programmed in R software. R software was selected due to its flexibility compared to other programming software. In addition, R provides a powerful platform for statistical computing and graphics (Torfs & Brauer, 2014).

The hydrologic model based on time-area method was developed as illustrated in Figure 2. In this regard, time-area diagram was developed by splitting catchment to sub-areas (using isochrones) with equal time steps (O'Loughlin & Stack, 2014). The routing procedure used in time-area method computes flow time from each sub-area individually depending on the physical properties. After each time period, the partial flow is calculated by the product of effective rainfall and the contributing sub-area of the catchment. At the end, the counted separate partial flow was lagged based on the given lag time and summed together to develop final hydrograph at discharge point as illustrated in Figure 2.

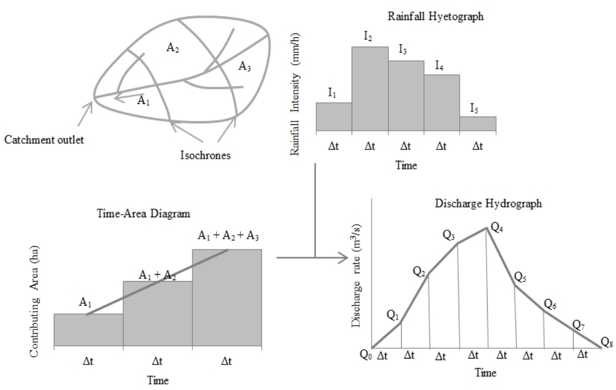

Figure 2. Time-area routing model (adopted from O'Loughlin & Stack, 2014)

Water quality model was programmed in R software based on pollutant build-up and pollutant wash-off processes models. A number of mathematical formulas have been suggested to replicate pollutant build-up process (Ball et al., 1998; Egodawatta et al., 2009). Among them, the power function of the build-up replication equation for road surfaces was taken as appropriate for this study and presented in Equation 1 (Egodawatta et al., 2009). Exponential form of wash-off equation was first proposed by Sartor et al. (1974). Wash-off equation shown in Equation 2 was the modified form of wash-off by Egodawatta et al. (2009) by introducing a new term called capacity factor (CF). They argued that pollutant removal from impervious surfaces is varied for different rainfall intensities and represented in the form of capacity factor (CF).

$$B = aD^b \qquad (1)$$

Where, B = Build-up load on road surface (g/m^2), D = Antecedent dry days, a and b = Build-up coefficients.

$$W = C_F W_0 (1 - e^{-kIt}) \qquad (2)$$

Where, W_0 = Initial weight of the material of a given particle size (g/m^2), CF = Capacity factor, k = Wash-off coefficient, I = Rainfall intensity (mm/h), t = Rainfall duration (hr), W = Weight of material of a given particle size removed after time t.

2.4 Sensitivity Analysis

In this study sensitivity analysis was conducted on programmed model in R to identify the influence of seven parameters (IL, TC, RF, TL, a, b, k) in simulating peak flow, mean flow, total runoff volume and total suspended solid (TSS) load. In this regard, TSS was regarded as the indicator pollutant of water quality. The sensitivity analysis was performed for three selected study catchments separately. The initial values of selected seven parameters were taken from the review of previous studies and Mike Urban user manual (Liu et al., 2011; Egodawatta et al., 2009; URBAN, 2012; Egodawatta et al., 2013).

In general practice, relative sensitivity was used to approximate the sensitivity of selected parameters (White and Chaubey, 2005). The relative sensitivity as expressed in Equation 3 was adopted in this study due to its simple structure and interpretation of the results. Equation 3 accounts the sensitivity of each parameter separately to the overall model output by changing each parameter by 10% of initial value. Greater the value of S_r, sensitivity of the parameter was considered as high. Absolute value of S_r was used for interpretations due to the potential of resulting negative values.

$$S_r = \left|\left(\frac{p}{m}\right)\left(\frac{m_2 - m_1}{p_2 - p_1}\right)\right| \qquad (3)$$

Where, p = parameter value, m = predicted output, p_1, p_2 = initial value ± 10% of parameter, m_1, m_2 = corresponding predicted output.

3 Results and Discussions

Sensitivity analysis was performed in two phases using absolute relative sensitivity as illustrated in Equation 3. In first phase, sensitivity of hydrologic-hydraulic model parameters (IL, TC, RF and TL) were assessed by considering peak flow, mean flow and total runoff volume as model outputs. In second phase sensitivity of stormwater quality model parameters (a, b and k) were tested by considering total TSS load as model output. During sensitivity analysis, parameters were changed one at a time (increased or decreased by 10%) to understand the influence of each parameter on desired model output for three catchments separately. The analysis results are shown in Figure 3 to Figure 6.

As seen in Figure 3 to Figure 5, reduction factor (RF) was found most sensitive compared to initial loss (IL), time of concentration (TC) and time-lag (TL) in estimation of peak flow, mean flow and total runoff volume for study catchments. IL show higher sensitivity for Gumbeel compared to Alextown and Birdlife Park catchments. This variation is due to the influence of initial moisture content, catchment surface type and percentage of impervious surfaces on RF and IL (Liu et al., 2011). TC and TL influence the shape of runoff hydrograph and can vary with drainage path, catchment slope and area (McCuen et al., 1984). TC was found more sensitive in estimating peak and mean flow than runoff volume for Alextown compared to Gumbeel and Birdlife Park catchments. TL was found less sensitive for all three catchments as shown in Figure 3 to Figure 5. This is agreed with the subdivisions adopted in catchment model development where the variation of TL was limited within residential land use in estimation of desired output.

As seen in Figure 6, build-up rate (a) was found most sensitive compared to k and b in estimating TSS load for three catchments. This suggests that pollutant build-up rate (a) is site specific and can significantly influence by urban land use, road surface and climate condition, and traffic density within the study catchments (Liu et al., 2011; Vaze and Chiew, 2002). Miller (1999) argued that wash-off coefficient (k) is site dependent and can vary with rainfall intensity, catchment area and slope, and types of pollutants. The variation in sensitivity of k was found minimal for three catchments. Due to this k can be considered as a constant within the same residential land use. Time exponent (b) demonstrates some sensitivity in Gumbeel than Alextown and Birdlife Park catchments. This indicates that b can be influenced by urban form and increased with factors such as population density (Egodawatta and Goonetilleke, 2006).

Summary of the sensitivity analysis outcomes are shown in Table 1, where selected seven parameters were ranked based on Sr values from highest to lowest order. As seen in Table 1, rank 1 indicates the highest value of Sr among seven parameters for one particular output. The analysis outcome suggest that peak flow, total runoff volume and mean flow are most sensitive to reduction factor whilst the TSS load was most sensitive to build-up rate for three study catchments. Hence, any change in reduction factor and build-up rate will significantly influence the desired output in hydrologic-hydraulic and stormwater quality modelling. However, like as reduction factor and build-up rate other parameters should be determined properly to reduce gross errors in final output result.

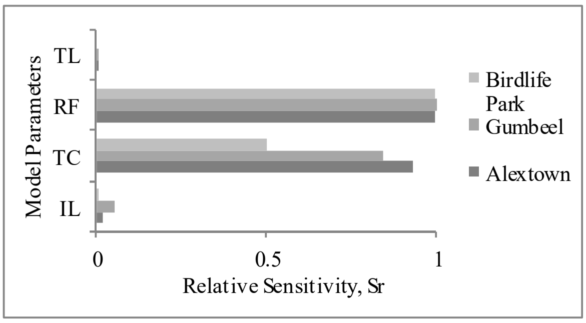

Figure 3. Sensitivity of model parameters for peak flow simulation

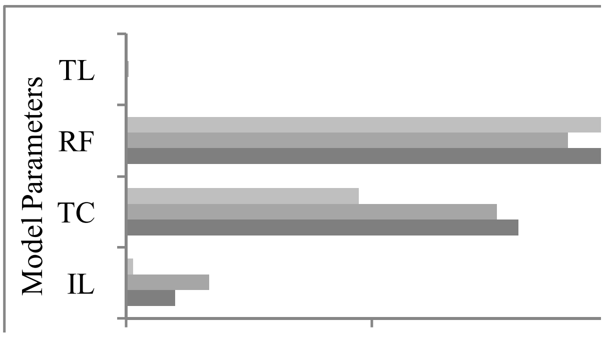

Figure 4. Sensitivity of model parameters for mean flow simulation

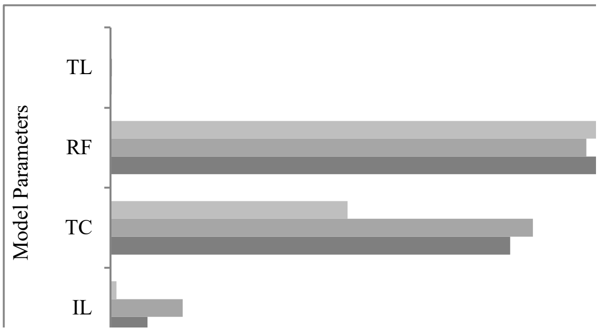

Figure 5. Sensitivity of model parameters for total runoff volume simulation

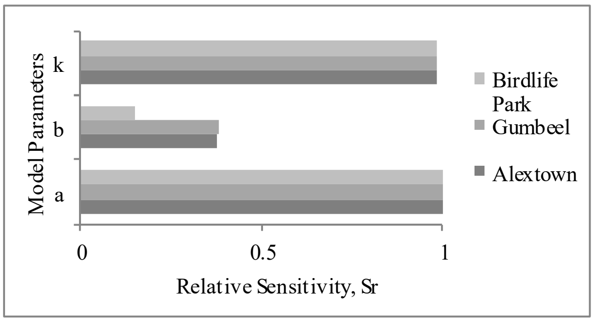

Figure 6. Sensitivity of model parameters for TSS load simulation

Table 1. Summary of sensitivity analysis results.

Particular output	Parameters rank			
	1	2	3	4
Peak flow	RF	TC	IL	TL
Mean flow	RF	TC	IL	TL
Total runoff volume	RF	TC	IL	TL
TSS load	a	k	b	-

Here, RF = Reduction factor, TC = Time of concentration, IL = Initial loss, TL = Time-lag, a = Build-up rate, b = Time exponent, k = Wash-off coefficient.

4 Conclusions

This paper represents outcomes of a study on sensitivity analysis of developed hydrologic-hydraulic and stormwater quality model parameters by considering peak flow, mean flow, total runoff volume and TSS load as model outputs. The approach adopted will help to assess sensitivity of model parameters in hydrologic, hydraulic and stormwater quality models enabling easy calibration. Based on the study results the following conclusions are drawn:

- Reduction factor (RF) was found as the most sensitive parameters in estimating peak flow, mean flow, total runoff volume while build-up rate (a) was found the most sensitive in estimating TSS load. The sensitivity of k did not vary significantly within the study catchments. This suggested the possibility of considering k as a constant within the same residential land use.
- TL was found insignificant in estimating peak flow, mean flow and total runoff volume estimation for study catchments. This concluded that the variation of TL was limited within residential land uses.

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