Sensitivity Analysis of Surface Runoff Parameters Towards Peak Discharge and Flood Volume

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Abstract. Inappropriate urban flood management may cause deterioration of urban living quality, known as urban decay. In order to avoid this, the sensitivity of surface runoff parameters towards peak discharge \((Q_p)\) and flood volume \((V_f)\) needs to be analysed. By conducting sensitivity analysis, the influence of any runoff parameter to these two output can be assessed quantitatively. This study aims to sort out the sensitivity of seven runoff parameters towards \(Q_p\) and \(V_f\) at part of the suburb of Mawson Lakes, South Australia. Four synthetic rainfall events with the Annual Recurrence Interval (ARI) of 2-year and 50-year; each with the duration of 12-hour and 72-hour; were generated by the AusIFD software. The hourly intensity values of these synthetic rainfall were then fed into the Storm Water Management Model (SWMM) to predict \(Q_p\) and \(V_f\). Further, the initial values of runoff parameters based on previous studies were used in the first flood estimation. Different sets of parameters which were 25% less than and greater than the initial values were used in the next flood modelling. Results showed that the most sensitive parameters were \% impervious followed by Manning’s \(n\)-pervious. Modelling using initial values of parameters produced \(Q_p\) and \(V_f\) of 0.340 m\(^3\)/s and 2.372 MCM for 2-year ARI respectively, whereas the corresponding values for 50-year ARI were 0.519 m\(^3\)/s and 3.424 MCM, respectively. Decreasing the parameter initial values by 25% produced. Meanwhile, increasing the parameters’ initial value by 25%.

1. Introduction

Appropriate urban flood management can be used to avoid the negative impact of flooding to the urban and its surrounding area. Peak flow \((Q_p)\) and flood volume \((V_f)\) are two of the most common output used in urban flood management. Previous studies showed that these output were influenced to different extent by runoff model’s parameters.

Mawson Lakes is a South Australia’s suburb which is currently under rapid development. Many real estates have been built including those in the vicinity of University of South Australia. Rapid land use change from natural catchment to residential land use might alter the runoff parameters and, in turn, could also influence the flood peak discharge and flood volume.

The present work is aimed to work out the sensitivity of selected runoff model parameters towards flood peak discharge \((Q_p)\) and flood volume \((V_f)\). The first step was analysing design rainfall by the Australian Intensity-Frequency-Duration (AusIFD) model, followed by simulating rainfall-runoff model using selected sets of the Storm Water Management Model (SWMM) parameter values, and finally conducting sensitivity analysis of the SWMM parameters towards peak discharge and flood volume.
2. Methodology

2.1. Study area

Part of Mawson Lakes suburb is presented in Figure 1. The study area is divided into 4 catchments by both Mawson Lakes Boulevard and Garden Terrace. There is only one rainfall gauge used in the SWMM model layout, namely Mawson Lakes gage. The study area was conceptualized using a layout depicted in Figure 2.
2.2. Rainfall input using AusIFD

AusIFD is a free software enable to calculate event rainfall intensity as well as its distribution patterns across Australia. AusIFD was developed by [1] at School of Environmental Engineering, Griffith University, Nathan, Queensland. AusIFD adheres Australian Rainfall and Runoff (ARR) 1987 [2], Chapter 2 and 3 by assuming log-normal rainfall intensity, two regional factors F2 and F50 and mean of regional skewness.

The first step in utilising AusIFD is choosing the study location from the available prescribed maps. Average rainfall intensity can be determined once the ARIs are selected. Rainfall duration vary from 5 minute to 72 hours whereas ARI are available from 1 to 100 years. The calculated rainfall intensities are depicted in graphs and/or presented in tables.

Standard ARIs employed in Australia are 2-year and 50-year, while the baseline rainfall duration are 12-hour and 72-hour. Hence, there were four synthetic rainfall events calculated as input for further flood simulations. Details required for calculating these rainfall intensities included latitude, longitude, skewness factor and regional factors; all were taken from AusIFD and were summarised in Table 1. In the present work, the study area was assumed to be represented by the nearest state capital city i.e. Adelaide.

| Location  | Adelaide  |
|-----------|-----------|
| State     | South Australia |
| Latitude  | 34.93 LS (cek) |
| Longitude | 138.60 BT (cek) |
| Skewness factor (G) | 0.57 |
| Regional factor F2 | 4.47 |
| Regional factor F50 | 14.95 |

2.3. Flood simulation by USEPA SWMM

Storm Water Management Model (SWMM) was developed by United States Environmental Protection Agency (USEPA). The model employs dynamic rainfall-runoff model to simulate both quantity and quality of urban runoff. Furthermore, SWMM simulates aspects of urban hydrology and water quality...
cycle such as rainfall, snow, runoff, drainage water flows and storage. SWMM can be utilised for both continuous simulation or single event [3].

Elements of hydrologic cycle in SWMM can be computed in quite various techniques. Infiltration, for instance, can be calculated by Green-Ampt, Horton or SCS method. Evaporation rate can be expressed as a constant, average monthly or other timescales chosen by the modellers. Rainfall is converted to runoff by unit hydrograph described by three parameters: portion of rainfall which enters the study area (R), time to peak (t) and ratio of recession time and time to peak notated by K.

Runoff routing is done using non-linear reservoir routing technique. Rainfall at upstream is the main input to SWMM while the output include infiltration, runoff and evaporation. Catchment runoff area can be worked out by subtracting runoff depth from maximum depression storage (d_p).

In SWMM, groundwater component is modelled in two zones. The first zone is unsaturated with the soil moisture denoted by \( \theta \), while the second zone is saturated and located beneath the first zone with the soil porosity denoted by \( \Phi \). Once the infiltration, evapotranspiration, percolation and lateral flow are calculated, a mass balance equation for change in groundwater storage in each zone is then developed. Calculation of the groundwater balance equation is solved in an iterative manner.

In the present work, Horton method and Kinematic Wave method were chosen for calculating infiltration and flood routing, respectively, with 15-second time interval. Rainfall was assumed concentrated in the study area’s centroid which then entered the drainage junctions. Runoff then flowed in closed conduits which was circle in shape with a diameter of 1-metre and roughness of 0.01 before eventually collected at an outfall. The details of junction and outfall were summarized in Table 2.

| Subcatchment/node | Land use  | Runoff coefficient | Junction | Conduit |
|-------------------|-----------|---------------------|----------|---------|
| S1                | Industrial| 0.70                | J1       | C1      |
| S2                | Open space| 0.50                | J2       | C2      |
| S3                | Residential| 0.60              | J3       | C2      |
| S4                | Residential| 0.60              | J4       | C1      |

2.4. Sensitivity analysis

[4] calibrated and verified two rainfall-runoff model parameters namely pervious depression storage and percent imperviousness using ten historic rainfall data at a 10-square mile residential area in Dallas, Texas. Their study revealed that rainfall depth was most sensitive to the two parameters but least sensitive to the space conceptualisation. In addition, calibration and verification by using percent imperviousness produced better results than using the two parameters.

[3] conducted sensitivity analysis by changing a parameter’s value while held the other parameters’ value constant. The study area is the 217 km² Ballona catchment located in Los Angeles. The study catchment consisted of residential area, natural catchment and industrial area. Calibration and verification were conducted based on 10 rainfall events in winter utilising Box optimisation algorithm. Four parameters were selected including the catchment imperviousness, the catchment width, pervious depression storage coefficient and Manning roughness (n). According to [3], the goal of sensitivity analysis is to seek the impact of altering a parameter value towards the desired output. Percentage impervious and depression storage, for instance, had greatest impact on peak discharge and flood volume whereas Manning’s n had the least impact as revealed in a study by [3].

Another study by [5] was aimed to determine the parameter that needed to be estimated with the highest accuracy as this parameter had the most important impact on the desired output. Sensitivity of four costing parameters were assessed against the total cost of a water treatment installation. The optimum parameter values were found first, and the procedures were repeated by decreasing the parameters values by 25% once at a time, while holding the other three parameters constant. Next, the
parameters’ values were increased by 25% one at a time while keeping the other three parameters constant. The total costs for each scenario was calculated and compared against each other. It was concluded that the total cost was most sensitive to the power coefficient function (a), followed by function power (b), interest rate (i) and timescales (g).

Sensitivity analysis was conducted to seven SWMM model parameters namely catchment percent slope, % impervious, impervious Manning roughness, pervious Manning roughness, impervious depression storage, pervious depression storage and % zero impervious. Default parameter values were fed into SWMM first, followed by underestimate and overestimate scenarios. In underestimate scenario, the default parameter values were decreased by 25% whereas in the overestimate scenario the default parameter values were increased by 25%. In both scenarios, one parameter was decreased or increased once at a time while the other parameter values were kept constant.

3. Results and Discussion

3.1. Design rainfall intensity

Based on the details given in Table 1, 30-minute design rainfall intensity can be calculated. Two sets of rainfall intensities were evaluated here, i.e. the first one is 2-year ARI, 12-hour duration and the second one is 50-year ARI, 72-hour duration. The distribution of design rainfall intensity in 30-min is given in Table 3.

| 30-min period | i (mm/hr) | 30-min period | i (mm/hr) | 30-min period | i (mm/hr) |
|---------------|-----------|---------------|-----------|---------------|-----------|
| 1             | 12.22     | 9             | 1.18      | 17            | 0.78      |
| 2             | 3.84      | 10            | 1.10      | 18            | 0.75      |
| 3             | 2.72      | 11            | 1.03      | 19            | 0.73      |
| 4             | 2.13      | 12            | 0.97      | 20            | 0.70      |
| 5             | 1.79      | 13            | 0.93      | 21            | 0.68      |
| 6             | 1.56      | 14            | 0.88      | 22            | 0.66      |
| 7             | 1.40      | 15            | 0.84      | 23            | 0.64      |
| 8             | 1.27      | 16            | 0.81      | 24            | 0.62      |

3.2. Flood simulation

Peak discharge and flood volume for default parameter values were summarized in Table 4 below. The default parameter values here were based on the SWMM manual authored by [6].

| Parameters                  | Default values | 2-year ARI, 12-hour duration | 50-year ARI, 72-hour duration |
|-----------------------------|----------------|------------------------------|--------------------------------|
| % slope                     | 0.50           | Q_p (m^3/s)                  | V_r (MCM)                      |
| % impervious                | 25.00          |                              |                                |
| Manning’s n pervious        | 0.10           |                              |                                |
| Manning’s n impervious      | 0.01           | 0.340                        | 3.424                          |
| Depression storage pervious | 0.05           | 3.424                        | 0.519                          |
| Depression storage impervious | 0.05          |                              |                                |
| % zero impervious           | 25.00          |                              |                                |

Peak discharge and flood volume for underestimate scenario and overestimate scenario were given in Table 5 and Table 6, respectively.

| Parameters                  | Default values | 2-year ARI, 12-hour duration | 50-year ARI, 72-hour duration |
|-----------------------------|----------------|------------------------------|--------------------------------|
| % slope                     | 0.50           | Q_p (m^3/s)                  | V_r (MCM)                      |
| % impervious                | 25.00          |                              |                                |
| Manning’s n pervious        | 0.10           |                              |                                |
| Manning’s n impervious      | 0.01           | 0.340                        | 3.424                          |
| Depression storage pervious | 0.05           | 3.424                        | 0.519                          |
| Depression storage impervious | 0.05          |                              |                                |
| % zero impervious           | 25.00          |                              |                                |
In order to assess the sensitivity of parameter towards the flood simulation outputs, the results in Table 5 and Table 6 were compared with those of Table 4. The differences of $Q_p$ and $V_f$ between underestimate scenario and overestimate scenario with those using default parameter values are presented in Table 7 and 8, respectively. Maximum differences (most sensitive) were typed in bold.

| Parameters | Default values | 2-year ARI, 12-hour duration | 50-year ARI 72-hour duration |
|------------|---------------|-----------------------------|-----------------------------|
| % slope    | 0.375         | 0.323                       | 0.491                       | 3.416                       |
| % impervious | 18.750      | 0.302                       | 2.219                       | 0.468                       | 3.257                       |
| Manning’s n pervious | 0.075      | 0.379                       | 2.387                       | 0.578                       | 3.441                       |
| Manning’s n impervious | 0.0075 | 0.341                       | 2.373                       | 0.519                       | 3.425                       |
| Depression storage pervious | 0.0375 | 0.341                       | 2.374                       | 0.519                       | 3.427                       |
| Depression storage impervious | 0.0375 | 0.340                       | 2.372                       | 0.519                       | 3.425                       |
| % zero impervious | 18.750      | 0.340                       | 2.372                       | 0.519                       | 3.424                       |

Table 7. Percentage of differences between using default parameter values and underestimate scenario

| Parameters | 2-year ARI, 12-hour duration | 50-year ARI 72-hour duration |
|------------|-------------------------------|-------------------------------|
| % slope    | -5.000                        | -5.395                        |
| % impervious | -11.176              | -9.827                        |
| Manning’s n pervious | 11.471 | 0.632                       | 11.368                       |
| Manning’s n impervious | 0.294      | 0.042                       | 0.000                       | 0.029                       |
| Depression storage pervious | 0.294      | 0.084                       | 0.000                       | 0.088                       |
| Depression storage impervious | 0.000      | 0.000                       | 0.000                       | 0.000                       |
| % zero impervious | 0.000      | 0.000                       | 0.000                       | 0.000                       |

Table 8. Percentage of differences between using default parameter values and overestimate scenario
4. Conclusion and Recommendation

Appropriate urban flood management is pivotal to avoid urban decay. Two modelling output which have got attention the most in urban flood management are flood peak ($Q_p$) and flood volume ($V_f$). These output can be managed by better understanding of selected urban flood model parameters, where the most sensitive parameters can be sorted out by means of sensitivity analysis.

Part of Mawson Lakes suburb of South Australia was chosen as the study area with two design rainfall intensity as the input to SWMM model. The first set was 2-year 12-hour duration rainfall intensity while the second one was 50-year 72-hour duration rainfall intensity. Three parameter sets were fed into the SWMM model in order to work out which parameters were $Q_p$ and $V_f$, the most sensitive to as well as the least sensitive to. In the first modelling attempt, all parameters were set at their respective default values whereas at the second and third attempt all parameters were set to be 25% less than the default values (underestimate scenario) and 25% greater than the default values (overestimate scenario), respectively.

In underestimate scenario with 2-year ARI 12-hour duration design rainfall intensity as the input, two parameters namely %-impervious and Manning’s n-pervious were shown to be the most important parameters in calculating $Q_p$ and $V_f$. Decreasing %-impervious by 25% of its default values reduced $Q_p$ by 11.176% whereas doing so to Manning’s n-pervious produced $Q_p$ which was 11.471% greater than using the default value. Flood volume was shown to be only sensitive to Manning’s n-pervious with 6.45% in reduction. Meanwhile, by feeding 50-year ARI 72-hour duration event rainfall intensity reduced $Q_p$ by 9.827% by lowering %-impervious and multiplied $Q_p$ by 11.368% by lowering the Manning’s n-pervious. Flood volume $V_f$ was only sensitive to %-impervious with 4.877% in reduction.

Overestimate scenario with 2-year ARI 72-hour duration event rainfall intensity showed similar results in calculating $Q_p$. Decreasing %-impervious by 25% resulted in 11.471% lower $Q_p$, whereas doing the same to Manning’s n-pervious produced lower $Q_p$ by 7.647%. Manning’s n-pervious was the only important parameter in predicting flood volume by addition of 6.366% flood volume. In 50-year 72-hour event, lowering %-impervious and Manning’s n-pervious produced lower $Q_p$ by 9.634% and greater $Q_p$ by 8.285%, respectively. Only %-impervious was also pivotal in predicting flood volume by the reduction of 4.848%.

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