

Calibration of urban stormwater drainage models using hydrograph modelling

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Use of mathematical models requires the estimation of model parameters, which is usually known as the calibration of the model. In general, parameter optimization is preferred in model calibration to the trial-and-error visual comparison of observed and modelled output responses, due to subjectivity and the time-consuming nature of the latter approach. An optimization procedure, called two-stage inner/outer optimization, is described in this paper, which can be used to estimate the model parameters of any urban stormwater drainage catchment modelled with any urban drainage computer modelling software. However, the ILSAX computer software was used in this study. The method is designed to provide the ‘best’ set of model parameters that consider several storm events simultaneously. Impervious area parameters are obtained from frequent ‘small’ storm events, while the pervious area parameters are obtained from less-frequent ‘large’ events. The Giralang catchment in Canberra (Australia) was used to demonstrate the method. Several ‘small’ and ‘large’ storm events of the catchment were considered in parameter optimization. Few other storm events, which were not used in model calibration, were used to validate the model parameters obtained from calibration. Results from both calibration and validation showed that the ‘best’ set of model parameters obtained for the catchment was able to produce hydrographs similar to the observed hydrographs. Pervious and impervious area parameters obtained from calibration agreed well with the information gathered from other sources such as aerial photographs and published literature.

Keywords: Calibration; Directly connected impervious area; Hydrograph modelling; ILSAX model; Parameter optimization; Pervious area parameters; Rainfall/runoff plots; Urban drainage

1. Introduction

Urban drainage simulation models, which consider hydrologic and hydraulic processes, are often used to plan, design and upgrade urban stormwater drainage systems. In order to use these simulation models, it is necessary to estimate the model parameters relevant to the urban drainage system. The model parameters can be accurately and

reliably estimated from calibration of the models, if the catchments are monitored for rainfall and runoff (i.e. gauged). However, calibration is not possible for ungauged systems. If regional equations, correlating model parameters to drainage system and other details, are available, they can be used to estimate the model parameters for ungauged drainage systems. To develop such regional equations, it is necessary also to estimate the model

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parameters for gauged catchments in the region through calibration.

Calibration of these urban drainage simulation models can be performed by trial-and-error visual comparison of modelled and observed hydrographs, or through a parameter optimization method. In the trial-and-error approach, the calibration parameters are obtained by conducting several model runs with different parameter sets and then selecting the 'best' parameter set, which produces the best match between modelled and observed hydrographs. This brings in a subjective element to the calibration process. Moreover, the trial-and-error approach is time-consuming and can often miss the 'optimum' parameter set. Parameter optimization, on the other hand, eliminates these weaknesses and produces the 'optimum' parameter set based on a user-specified objective function, after searching through the whole domain of the model parameters. The parameter optimization method is used in this study to estimate the model parameters of urban drainage models.

An optimization procedure called two-stage inner/outer optimization is described in this paper, which can be used to estimate model parameters of any urban drainage catchment modelled using any urban drainage modelling software. However, the ILSAX computer software (O'Loughlin 1993) was used in this study. The method is designed to provide the 'best' set of model parameters that consider several storm events simultaneously. It considers all attributes of the hydrographs (i.e. runoff volume, runoff peak, time to peak and shape) at the catchment outlet. The impervious area parameters are obtained from frequent 'small' storm events, while the pervious area parameters are obtained from less-frequent 'large' events. The Giralang catchment in Canberra (Australia) was used to demonstrate the method.

First, the ILSAX model and its model parameters are briefly discussed in the paper. Then, it discusses the study catchment and the selection of rainfall/runoff events used for calibration and validation. The two-stage inner/outer optimization procedure is described, followed by the estimation of model parameters for the Giralang catchment through this optimization procedure. The validation of the optimized model parameters is discussed. Finally, the conclusions drawn from the study are presented.

2. ILSAX model and model parameters

ILSAX (O'Loughlin 1993) is a rainfall/runoff model that can be used to design and analyse urban drainage systems. In order to use ILSAX, the catchment is first divided into several subcatchments based on land use and other physiographic conditions. Each subcatchment may consist of three surfaces, namely paved areas (sometimes called directly connected impervious areas), supplementary im-

pervious areas and grassed areas. In ILSAX (and most other urban drainage modelling software), the paved and grassed areas are directly connected to the drainage system, while the supplementary areas, which are also impervious areas, are not connected directly to the drainage system. The runoff from the supplementary areas flows over pervious surfaces before reaching the drainage system. Figure 1 shows the ILSAX modelling representation of an urban catchment, showing various components of the drainage system such as inlets, pipes and detention storage, and the flow paths. More details of ILSAX can be found in O'Loughlin (1993).

ILSAX uses storm rainfall as input, subtracts rainfall losses in each surface of the subcatchment, and routes the resultant rainfall excess from each subcatchment surface to the inlet and then through the pipe system, to the outlet. This process differs from surface to surface in the way the loss is modelled. For paved areas, the loss is due to paved area depression storage, while for pervious areas, the pervious area depression storage and infiltration losses need to be considered. The Horton infiltration equation is used in ILSAX to model the pervious area infiltration loss. The supplementary impervious area is modelled by adjusting rainfall intensities falling in the pervious area. The conversion of catchment rainfall into runoff at the catchment outlet is detailed in O'Loughlin (1993).

Like any other mathematical model, the ILSAX model has its own model parameters. The ILSAX model is conceptualized in figure 2, showing its model parameters. The model parameters can be divided into two main groups. The first group deals with the parameters responsible for the rainfall excess. The second group accounts for routing parameters of pervious and impervious areas, and drainage pipes and channels. In this paper, these two groups are loosely termed hydrological and routing parameters, respectively. The hydrological parameters are the pervious area depression storage (DS_p), the impervious area depression storage (DS_i) and the soil curve number (CN). It should be noted, however, that CN in ILSAX is different to the runoff curve number of US Soil Conservation Service Method in estimating surface runoff. The CN in ILSAX refers to the numerical classification of soils developed by the US Department of Agriculture, as described in Chow (1964), while the runoff curve numbers are related to both soil type and cover (Soil Conservation Service 1968). The parameters CN and antecedent moisture condition (AMC) together define the infiltration process of pervious areas. However, it should be noted that AMC is not a model parameter of the catchment and is an event-dependent parameter, since it represents the catchment moisture content before the storm. Therefore, it differs from event to event. The AMC determines the start of the hydrograph. The routing parameters are the Manning's friction coefficient of pipes (N_p), the retardance coefficient

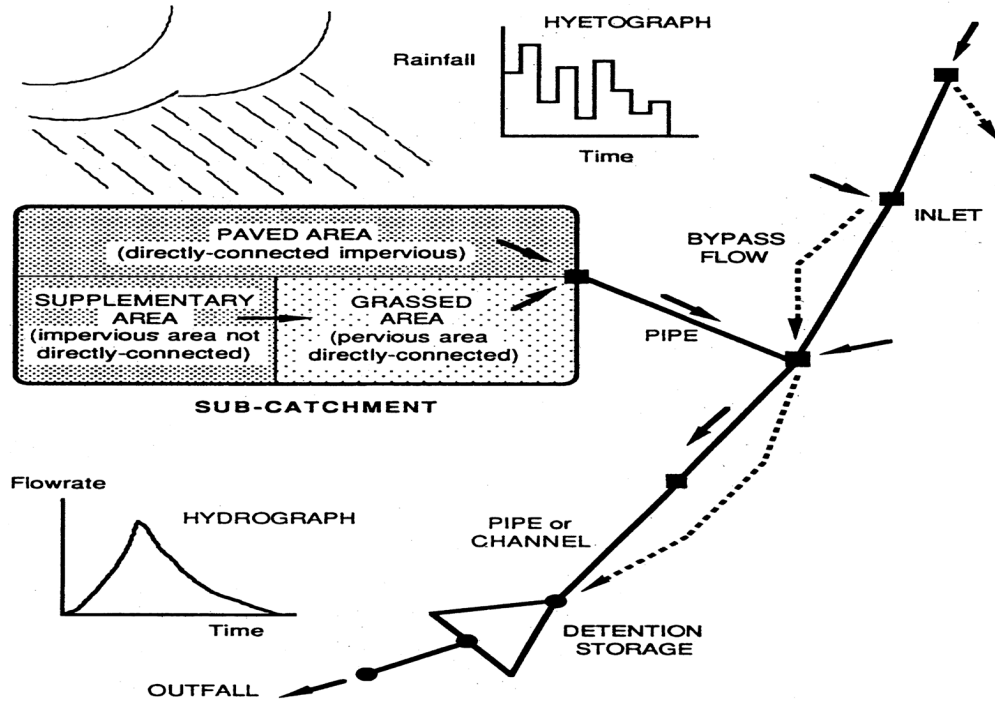


Figure 1. ILSAX representation of a catchment (O'Loughlin 1993).

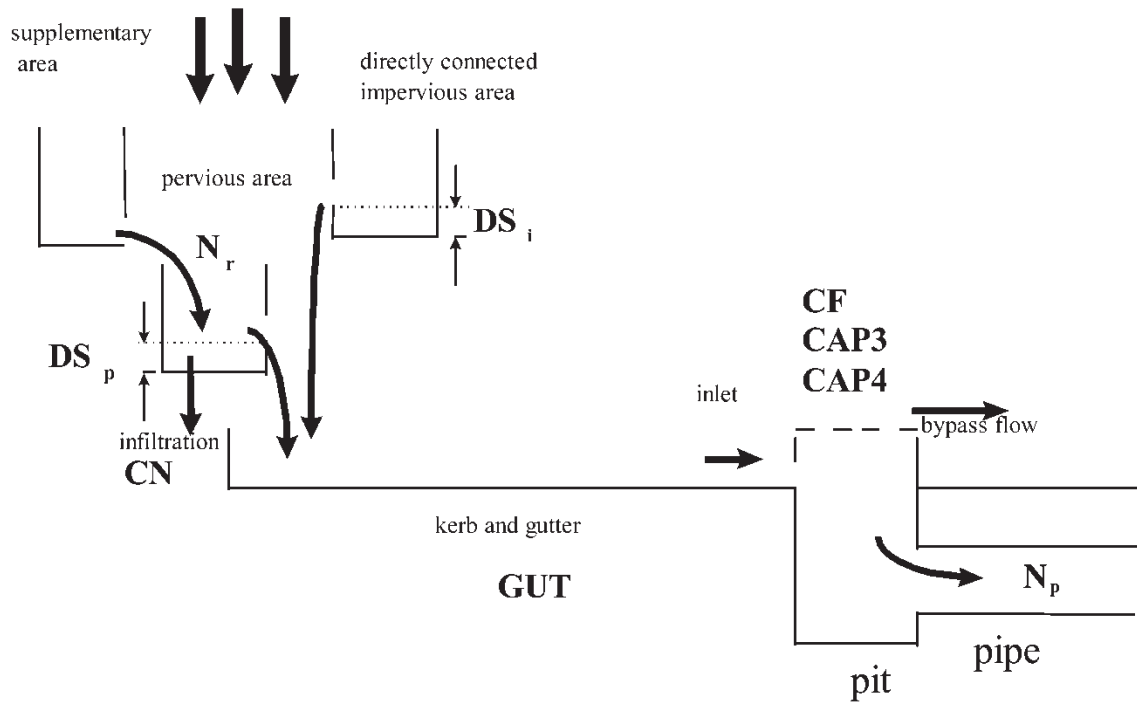


Figure 2. ILSAX model parameters.

of pervious areas (N_r) and the choke factor (CF). Additionally, the gutter flow factor (GUT) and two pit

capacity parameters (i.e. CAP3 and CAP4) for grade pit inlets are also considered as routing parameters, as shown

in figure 2. Although the sag pits can be modelled with ILSAX, they are not shown in figure 2, since they were not present in the study catchment described in this paper.

GUT can be estimated from hydraulic data of the gutters. Similarly, the pit capacity parameters can be obtained from published literature, which are based on physical hydraulic modelling tests. Therefore, GUT and pit capacity parameters can be considered as data in modelling an urban drainage system. However, they should be accurately estimated, since they affect the output response of the model.

The hydrological parameters define the rainfall excess, and depend on specific catchment characteristics (e.g. soil type, percent imperviousness and depression storage) and in some cases on rainfall characteristics. These parameters are sensitive to output responses such as runoff volume and peak of the hydrographs. The routing parameters describe flow routing in the catchment and the pipe/channel systems, and can affect the peak discharge and hydrograph shape. However, the uncertainty of these parameters is less compared to the hydrological parameters, and also the sensitivity of these parameters on runoff output responses is less compared to the hydrologic parameters. Moreover, the routing parameters can be estimated or extracted from literature easier than the hydrological parameters. Therefore, in this study, only the hydrological parameters were considered.

3. Study catchment

The study catchment used in this study was the Giralang catchment in Canberra in Australian Capital Territory (ACT). The drainage details used for modelling of the catchment were as of 1976, since there was no further urban development of the catchment after 1976. Aerial photographs and drainage plans prepared in 1976 were used to extract data for modelling. Similarly, data on storm events (i.e. rainfall hyetographs and corresponding hydrographs at the catchment outlet) after 1976 were used for modelling, to be compatible with the catchment conditions.

The catchment boundary and the drainage system of the Giralang catchment are shown in figure 3. The area of the catchment is 94 ha, and as estimated from aerial photographs, 24% of the catchment consists of impervious areas (which includes both directly connected impervious areas and supplementary areas). The average slope of the catchment is 4.8%. A flowmeter and three pluviometers measured flow at the catchment outlet and rainfall within the catchment.

Fourteen subcatchments were used to model the study catchment, as shown in figure 3. As can be seen from this figure, not all inlet pits and lateral drains were modelled with this subdivision. This subdivision scheme is generally termed the medium subdivision (Heeps and Mein 1973).

Details of the subcatchments are given in table 1. In each subcatchment, grassed and paved areas (which included supplementary areas) were measured separately from aerial photographs. In estimating flow path lengths of the subcatchments and their slopes, the overland, channel and pipe flow paths were considered, and they were measured from contour maps and drainage plans. These details are shown also in table 1.

4. Calibration and validation storm events

All data records related to rainfall in the catchment and flow at the catchment outlet were studied to select significant storm events for calibration and validation of the ILSAX model of the catchment. The rainfall hyetographs from the three pluviometers were averaged using Thiessen polygon method to produce the event hyetograph for the catchment. The rainfall data of these storm events and the corresponding runoff data were then checked for consistency in terms of matching rainfall and runoff volumes, preserving continuity and conforming temporal trends. These data-checking procedures are described in detail in Dayaratne (2000) and Maheepala *et al.* (2001). These significant storm events were further analysed for their suitability in calibration and validation, as described below.

The rainfall and runoff depth plots (i.e. RR plots) were used in this study to separate 'small' and 'large' storm events, and to estimate the directly connected impervious area percentage (DCIA) and its depression storage (DS_i), with respect to the total catchment. In these RR plots, the runoff depth is expressed as the ratio of runoff volume at the catchment outlet to the total area of the catchment. If an RR plot is obtained for 'small' events, theoretically it should be a straight line. The gradient of this line gives the directly connected impervious area percentage (DCIA). The depression storage (DS_i) of the directly connected impervious area is given by the intercept of this line with the rainfall depth axis. The RR plots have been used in the past mainly to estimate DCIA and DS_i . Examples include the studies of Kidd (1978), Bufill and Boyd (1992), Boyd *et al.* (1993), Zaman and Ball (1994), Dayaratne (1996, 2000), and Maheepala (1999).

An RR plot was initially constructed considering all significant storm events (both 'small' and 'large') of the Giralang catchment selected from the database. Figure 4 shows this RR plot. As can be seen from this figure, the storm events with fairly low rainfall and runoff depths follow a straight line, while the storm events with reasonably large rainfall and runoff depths deviate from this line. As Boyd *et al.* (1993) point out, the 'small' storm events, which are on the straight line, are generated from directly connected impervious areas, while the 'large' storm events, which deviate from the straight line, are

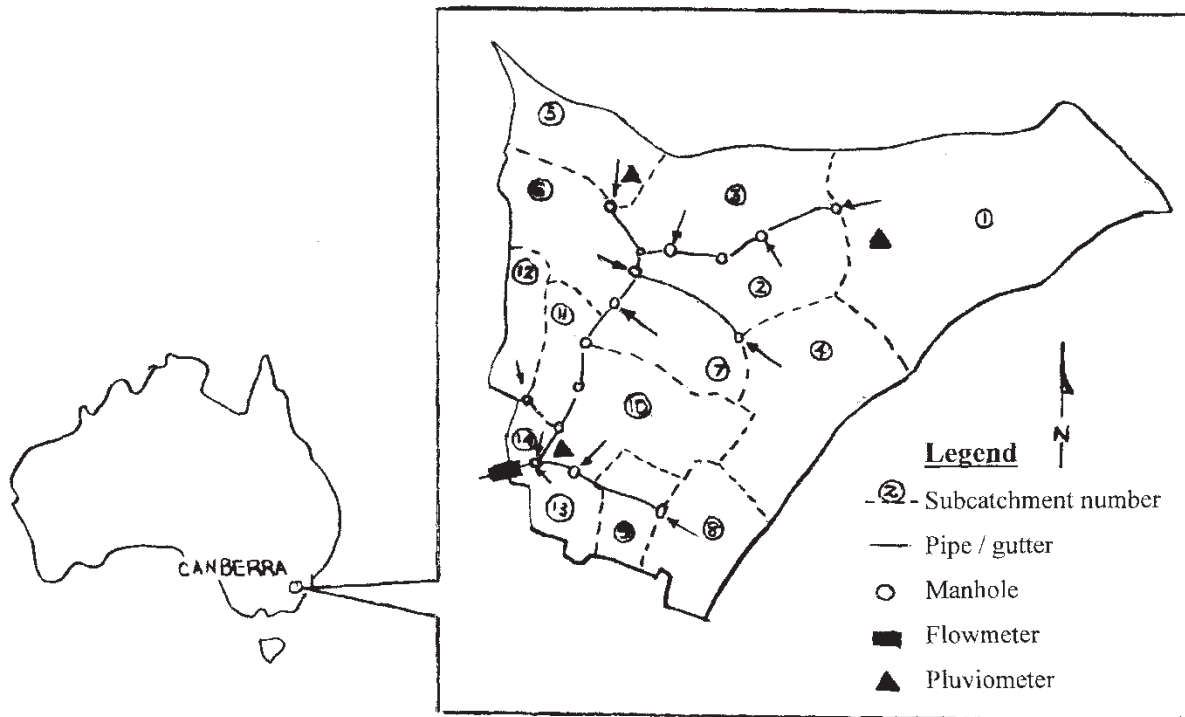


Figure 3. Giralang catchment in Canberra.

Table 1. Subcatchment properties of Giralang catchment.

Subcatchment no.	Total area (ha)	Grassed area (%)	Paved area (%)	Diameter of largest pipe (m)	Flow path length (m)			Slope (%)		
					Overland	Channel	Pipe	Overland	Channel	Pipe
1	24.64	90	10	N/A*	625	200	–	6.3	2.5	–
2	6.53	62	38	0.250	62	–	186	6.4	–	4.4
3	8.55	74	26	0.300	150	–	173	5.3	–	6.2
4	10.71	76	24	0.375	290	–	83	8.8	–	6.7
5	5.30	74	26	0.375	200	–	83	0.6	–	3.4
6	6.56	66	34	0.445	188	–	220	10.6	–	3.1
7	5.48	63	37	0.375	125	–	245	0.8	–	1.8
8	5.80	82	18	0.450	175	–	91	0.5	–	10.5
9	3.06	70	30	0.690	–	–	217	–	–	4.4
10	7.86	64	36	0.450	80	–	90	12.5	–	3.8
11	3.12	61	39	0.225	138	–	113	0.3	–	2.2
12	2.70	52	48	0.300	100	–	141	0.5	–	3.3
13	2.83	73	27	0.300	81	–	212	4.6	–	2.0
14	1.04	50	50	0.300	81	–	213	4.6	–	2.0

*Note: Subcatchment 1 only has an open channel.

generated from both impervious and pervious areas. The reason for this is that even for 'small' rainfall depths, the directly connected impervious area responds immediately after filling its depression storage. As rainfall depth increases, both supplementary impervious and pervious areas respond, in addition to the directly connected impervious areas.

The 'large' storm events, which show a significant departure from the straight line (in figure 4) were separated, and then the remaining events (i.e. 'small' events) were plotted again on a RR plot. This new RR plot is shown in figure 5. As seen from this figure, this plot shows a good correlation among data points. The DCIA and DS_i values were estimated as 19% and 0.26 mm, respectively, as

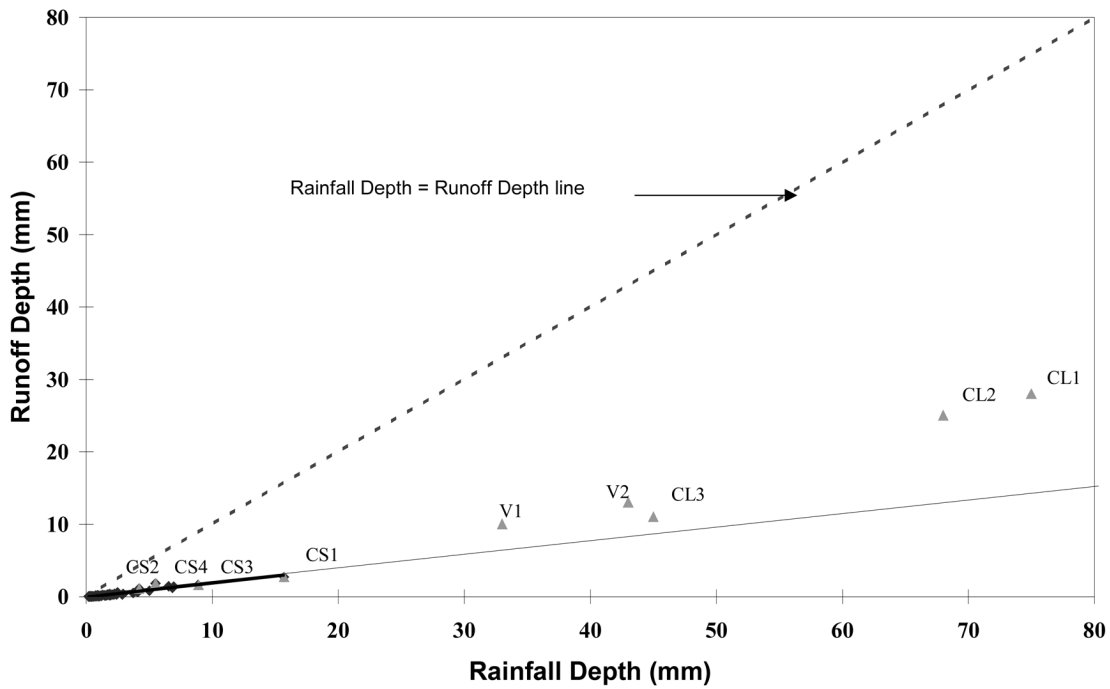


Figure 4. Rainfall and runoff depth plot for all selected storm events.

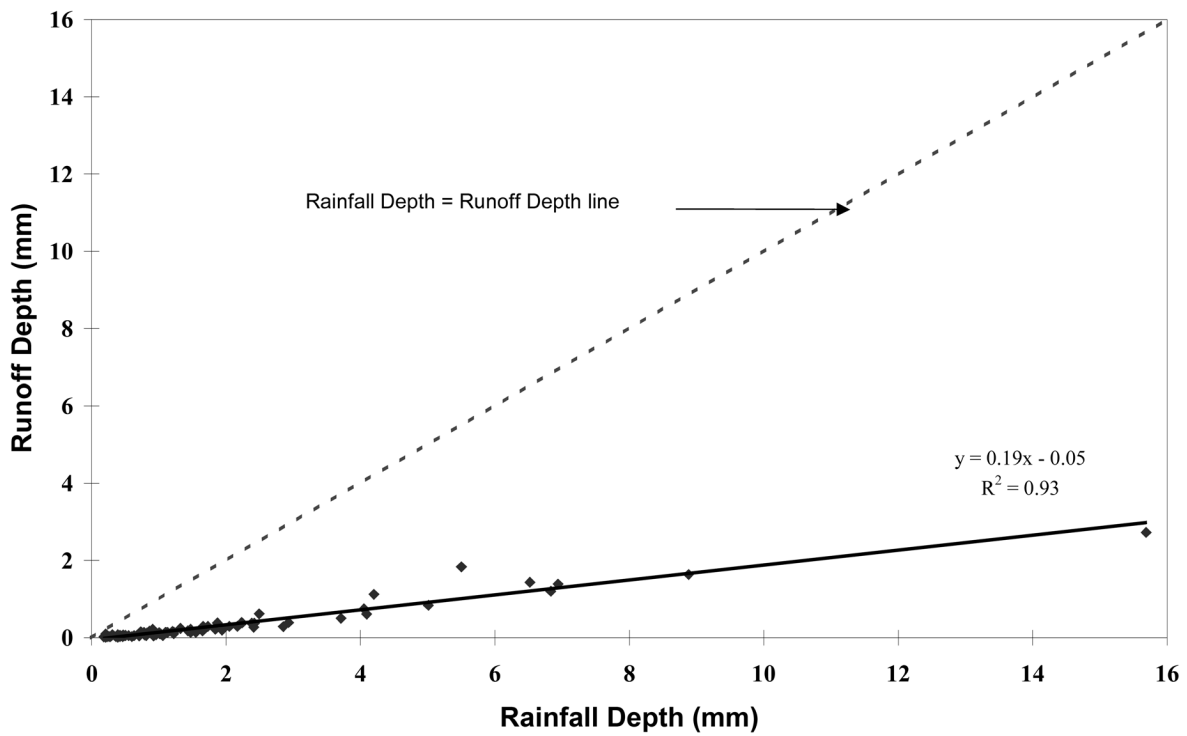


Figure 5. Rainfall and runoff depth plot after removing 'large' storm events.

discussed earlier in this section. Note that this DCIA deals only with the directly connected impervious areas, while

24% given in section 3 was estimated from aerial photographs, which includes both directly connected and

supplementary impervious areas. It should also be noted, however, that these DCIA and DS_i consider only the runoff volume, and that no consideration is given to the other attributes of the hydrographs such as peak discharge and time to peak, which are equally important in urban drainage design and analysis. Therefore, a hydrograph modelling approach was used in this study to refine model parameters obtained from the RR plot of the study catchment, and to estimate model parameters. This approach considers all attributes of hydrographs (i.e. runoff volume, peak discharge, time to peak and shape). These output responses are important for water resource planners in urban stormwater management.

From these RR plots, four 'small' storm events (i.e. CS1, CS2, CS3 and CS4) and three 'large' storm events (i.e. CL1, CL2 and CL3) were selected for model calibration. A further two events (i.e. V1 and V2) were selected for use in validation of the model parameters. The details of these selected nine events are given in table 2. These events are also shown in figure 4. The maximum rainfall intensity and the total rainfall depth of the storm events in table 2 were obtained from the event hyetographs. The stormwater runoff volume and the maximum discharge were obtained from the event hydrographs at the catchment outlet. As seen from table 2, there are significant differences in the ratio of runoff volume to rainfall volume of 'small' and 'large' calibration events and validation events (which are also 'large' events). This ratio should be approximately the same across the 'small' events. The difference could be due to localized initial losses through varying paved area depression storage or the fact that widespread rainfall may not have occurred over the whole catchment during these 'small' storm events. It should be noted that it was assumed that widespread rainfall occurred over the whole catchment in hydrograph modelling of this study.

5. Calibration procedure using hydrograph modelling

Ideally, mathematical models simulating the rainfall/runoff behaviour of catchments should have model parameters

that are measurable and have direct physical relevance to catchment processes. Given the conceptual nature of most mathematical models, including ILSAX, the values of some of these parameters cannot be obtained from field measurements. For example, the impervious area depression storage (DS_i) of ILSAX (and other urban drainage computer models) cannot be estimated through field measurements of the catchment. Therefore, a calibration strategy is required to estimate these model parameters, which are either impossible or difficult to measure. The goal of the calibration is to obtain the 'best' set of model parameters, which produces the best fit between measured and model-predicted output (in this case, the hydrograph at the outlet of the catchment) within a reasonable accuracy. This accuracy is considered by establishing a criterion of goodness of fit of the simulated hydrograph at the catchment outlet to that of the observed, irrespective of the calibration approach used (whether it is trial and error or optimization).

As outlined in section 1, an optimization strategy called two-stage inner/outer optimization was developed in this study, to yield the 'best' set of model parameters that considers several storm events simultaneously. This strategy is different to the common practice of selecting the single 'best' parameter set by 'averaging' the different parameter sets obtained from different calibration events (e.g. Kidd 1978, Dayaratne 1996, Muncaster *et al.* 1997). The 'averaging' method is satisfactory when there is only one model parameter that needs to be estimated. However, when there are several model parameters that need to be calibrated, the 'averaged' parameter set may not be the 'best' parameter set because of parameter interaction exhibited in most models.

As stated previously, urban catchments respond differently to storm events of different magnitudes. If urban catchment models are calibrated without considering the magnitude of storm events, the calibrated model parameters will be in error. 'Small' events produce runoff only from impervious areas. Therefore, only the impervious area parameters need to be considered when the models are

Table 2. Summary statistics of calibration and validation events.

Event properties	Calibration events						Validation events		
	'Small'				'Large'		V1	V2	
Event number	CS1	CS2	CS3	CS4	CL1	CL2	CL3	V1	V2
Date of occurrence	05.02.77	12.09.77	02.01.78	24.11.79	03.01.93	03.03.92	25.03.84	27.01.78	12.02.81
Total rainfall depth (mm)	15.7	4.2	8.9	5.5	75.2	69.3	40.3	33.5	42.7
Maximum rainfall intensity (mm/h)	52.0	12.0	50.0	38.0	97.2	121.2	94.8	54	36.0
Stormwater runoff volume (mm)	2.7	1.1	1.6	1.8	28.4	13.2	9.9	9.9	12.9
Maximum discharge (m^3/s)	1.44	0.73	1.77	2.34	7.12	4.98	6.21	4.65	2.81

calibrated with ‘small’ storm events. For ‘large’ storm events, runoff is generally produced from both pervious and impervious areas. However, the runoff generation mechanism from impervious areas still remains the same, as for ‘small’ storm events. Therefore, the impervious area parameters can be estimated first using ‘small’ storm events, and then the pervious area parameters using ‘large’ events, keeping the impervious area parameters obtained from ‘small’ events constant. These ideas are incorporated into a two-stage inner/outer optimization strategy. The procedure is schematically shown in figure 6.

According to this strategy, the parameter optimization was carried out in two stages. During Stage 1, the model parameters responsible for ‘small’ storm events (i.e. DCIA and DS_i) were obtained through optimization by linking the ILSAX model (with data related to each storm event) with the parameter optimization software, PEST (Watermark Numerical Computing, Australia 1998). The linking was done through input and output files of both software

packages, and has been successfully used in the past by Hill (1992) and Muncaster *et al.* (1997) in calibrating different simulation models.

PEST uses the Gauss–Marquardt–Levenberg method (Marquardt 1963) for parameter estimation. When PEST is used for nonlinear problems such as urban drainage models, the parameter estimation is done through an iterative process. At the beginning of each iteration, the relationship between model parameters and model-generated output is linearized using Taylor series expansion about the current best parameter set. The linearized problem is then solved for a better parameter set and the new parameter set tested by running the model again. By comparing the parameter changes and objective function improvement between two successive iterations, PEST determines whether another iteration is required. Otherwise, the optimum parameter set is achieved. The mathematical details of PEST can be found in Watermark Numerical Computing, Australia (1998).

This optimization through PEST is called the inner optimization in this paper and yields a set of optimized parameters of DCIA and DS_i corresponding to each ‘small’ storm event. The default objective function of PEST, which minimizes the sum of squared differences between modelled and observed hydrograph ordinates, was used in the inner optimization with equal weights for all hydrograph ordinates. As suggested by Johnston and Pilgrim (1976), squaring deviations provide the best means of forming the objective function. This objective function explicitly considers all hydrograph attributes (i.e. runoff volume, runoff peak, time to peak and shape). It should be noted that although DCIA can be physically measured (at least in theory) it requires the identification of individual properties that are connected to the drainage system. Generally, DCIA is estimated from the aerial photographs and includes supplementary areas. Therefore, these estimates provide a higher value than the correct DCIA for the catchment. For this reason, DCIA was considered as a calibration parameter in this study. Ghafouri (1996) and Choi and Ball (1999) suggested that DCIA should be considered as a calibration parameter in urban drainage models.

The outer optimization of Stage 1 was then carried out to select the ‘best’ parameter set from the individual ‘optimum’ parameter sets obtained from different storm events of the inner optimization. The ‘best’ parameter set is considered to be a compromised set considering all storm events and their output responses of runoff volume, peak discharge and time to peak. Under the outer optimization, each storm event is modelled using its own rainfall data and the different parameter sets obtained from different storm events. The output responses of runoff volume, runoff peak and time to peak of the hydrographs at the catchment outlet were noted for these model runs. The ‘best’

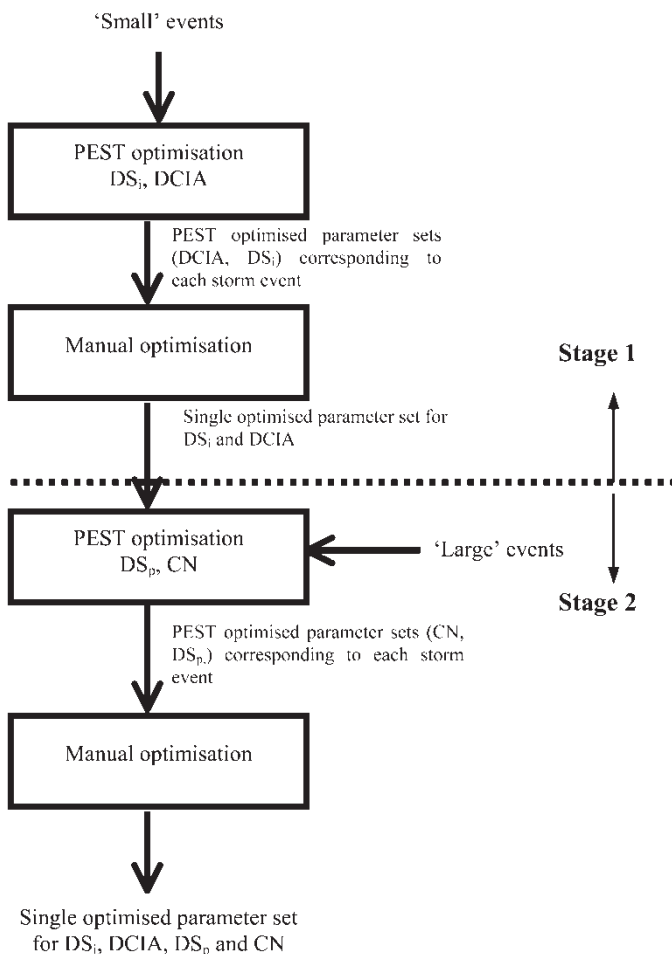


Figure 6. Two-stage inner/outer optimization procedure.

parameter set was then selected as the set, which produces the minimum sum of the absolute relative difference of these output responses of the hydrographs considering all storm events and all ‘optimum’ parameter sets. Mathematically, the objective function used in the outer optimization can be written as:

$$\text{Min}_k \sum_{j=1, N} \sum_{i=V, P, TP} \left| \frac{O_{i,j,k} - Ob_{i,j}}{Ob_{i,j}} \right| \quad (1)$$

where i is the variable representing runoff volume (V), runoff peak (P) and time to peak (TP), j is the variable representing storm events, k is the variable representing the ‘optimum’ model parameter sets due to different calibration events, $O_{i,j,k}$ is the modelled output response (i) of V , P or TP of storm event j corresponding to parameter set k , $Ob_{i,j}$ is the observed output response (i) of V , P or TP of storm event j , and N is the number of storm events.

The inner optimization (by linking PEST with ILSAX) was carried out automatically, while the outer optimization was conducted out manually. This inner/outer optimization procedure for Stage 1 gives the ‘best’ set of impervious area model parameters, which considers all attributes of the hydrographs with respect to all storm events analysed.

Stage 2 is similar to Stage 1, but considers only the pervious area parameters. It also uses the ‘large’ storm events. During the inner optimization of Stage 2, the pervious area parameters of DS_p and CN were optimized, keeping the ‘best’ impervious parameters set obtained from Stage 1 as constant. The AMC was not optimized in the inner optimization; rather, it was obtained for each storm event using the guidelines given in the ILSAX manual based on the 5-day rainfall totals prior to the event. This approach was used to reduce the number of parameters in optimization. Furthermore, the AMC affects only the start time of the hydrograph, and therefore can be easily determined. During the outer optimization, a similar procedure to Stage 1 was used. However, in this case, the model parameter set k consists of both impervious and pervious area parameters. The impervious area parameters are the ‘best’ parameters obtained from the outer optimization of Stage 1, and the pervious area parameters differ from storm event to event considered in the inner optimization of Stage 2. The AMC obtained earlier for each storm event was used to calculate $O_{i,j,k}$ (in the objective function) corresponding to that event. At the end of Stage 2, the ‘best’ parameter set (i.e. DS_i , $DCIA$, DS_p and CN) is obtained which can be considered as the ‘best’ parameter set satisfying all calibration storm events (both ‘small’ and ‘large’) and all attributes of the hydrographs (i.e. runoff peak, runoff volume, time to peak and hydrograph shape).

6. Calibration of model parameters for study catchment

6.1 Preliminaries

Before proceeding with calibration of model parameters, two issues were considered that were important for this particular application. They are described below.

6.1.1 Property time. The property time (i.e. the time for roof runoff of a property to reach the road gutter system) may have some effect on runoff hydrographs at the catchment outlet. For design, the Australian Rainfall and Runoff (The Institution of Engineers, Australia 1987) and the ILSAX manual (O’Loughlin 1993) recommend 5 min as the property time, while 2 min has been built into ILLUDAS-SA (Watson 1981), which is an earlier version of ILSAX. The only study found in the literature in relation to evaluation of hydrographs (i.e. simulation of catchment during actual storms) was that of Stephens and Kuczera (1999), which suggested 2 min as the property time for residential blocks. Therefore, a study was conducted to select the appropriate property time for the catchment for use in calibration of the ILSAX model.

For each calibration event of the catchment, the property time was initially assumed as 5 min and the corresponding hydrograph was obtained from the ILSAX model with reasonable values for model parameters such as the values obtained from RR plots (figure 5) and other sources. The simulated hydrograph was then visually compared with the observed hydrograph. Then, several other property times were used in an attempt to improve matching of observed and simulated hydrographs. The results with respect to all calibration events showed that modelling could not be consistently improved by changing the property time from 5 min (Dayaratne 2000) due to the reasons given below:

- The calibration events showed different results with respect to different property times. Some events even required the large property times (i.e. even larger than 5 min), while the others require smaller values, to match with the observed hydrographs.
- The events with multi-peaks showed different characteristics. In some events, the first peak required a higher property time, while the second peak required a lower property time. Other multi-peak events had the opposite effect.
- In some cases, the property time had to be increased to more than 10 min to match with the observed time to peak.

Since no strong evidence was found in this study to discard the property time as 5 min, the 5-min property time was considered in the calibration of the Giralang urban drainage catchment model.

6.1.2 Computational time step. The results of the computer models can be sensitive to the computational time step used in the calculations. O'Loughlin *et al.* (1998) studied the effect of different computational time steps on hydrographs and recommended the use 1 or 2 min as the computational time step for ILSAX. Therefore, a computational time step of 2 min was used for model runs in this study. This time step was further justified as the hydrographs were recorded at 2-min intervals.

6.2 Calibration

The two-stage inner/outer optimization procedure was used to obtain the 'best' parameter set for the study catchment. As stated in Section 4, four 'small' storm events were used for Stage 1 calibration. Like most parameter optimization methods, PEST requires the specification of starting values (or seeds) and a feasible range for the parameter set. DCIA and DS_i obtained from the RR plot (figure 5) were used as the seed for Stage 1 inner optimization. However, the numerical experiments conducted with different seeds did not produce different optimum parameter sets for selected storms. Ranges for DCIA between 0 and 24% and for DS_i of 0–2 mm were adopted in the PEST optimization. A value of 24% was considered as the upper range of DCIA, since this value was obtained from aerial photographs and includes both the directly connected impervious area and supplementary area. The range for DS_i is comparable with the results of previous studies (Danish Hydraulic Institute 1988, Bedient and Huber 1992, O'Loughlin 1993).

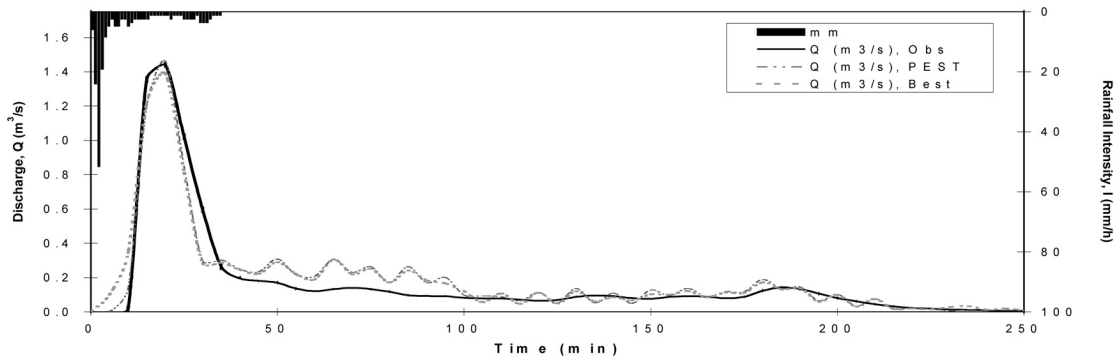
The PEST calibrated impervious area parameter values corresponding to the four 'small' storm events are given in table 3. The 'best' parameter set was then selected from the outer optimization. The parameter set corresponding to storm event CS2 (i.e. DCIA = 19 and $DS_i = 0$) was found to be the 'best' impervious area parameter set for the study catchment. The calibration plots of the four 'small' storm events are shown in figure 7. These plots show the rainfall hyetograph of the storm event, the corresponding observed hydrograph at the catchment outlet, and the modelled hydrographs using the PEST calibrated parameter set (i.e. 'optimum' parameter set obtained from this event) and the 'best' parameter set. Table 4 shows the observed and modelled peak discharge and runoff volume for 'small' events used in calibration. It also shows this information for 'large' events used for calibration and storm events used for validation (section 7). Modelled peak discharge and runoff volume in table 4 are based on 'best' parameter set.

As can be seen from figure 7, the hydrograph shapes of all four events were satisfactorily modelled with both 'PEST' and 'best' parameter sets. As evident from table 2, these events are small storm events with a small runoff volume. For small events, the effect of DS_i on runoff hydrograph is more important than the effect of DCIA, as

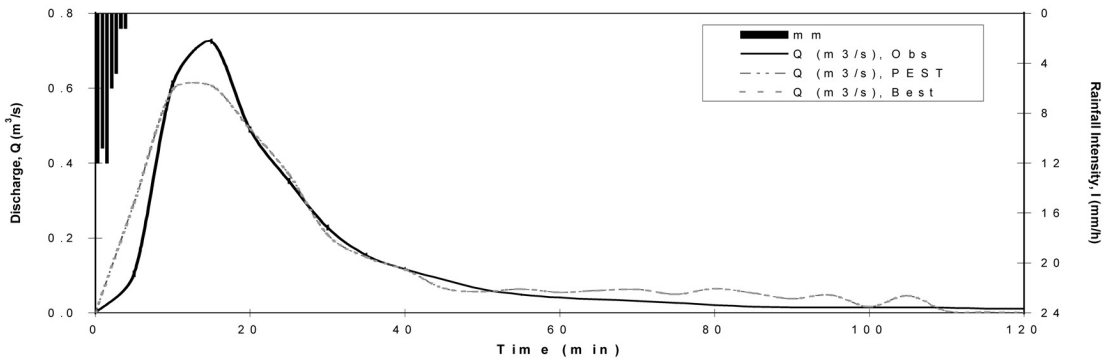
seen from figure 7 by comparing hydrographs with PEST and 'best' parameter sets. Overall, the event CS1 was modelled extremely well. Even the event CS2 was modelled satisfactorily and the difference in peak discharge was only about $0.1 \text{ m}^3/\text{s}$. The events CS3 and CS4 were not modelled that well. It is possible to obtain the modelled hydrograph in the event CS3 close to the observed by increasing DS_i . This will improve the start time of the hydrograph and possibly reduce the peak, but increasing DS_i beyond 2 mm is not reasonable. In the event CS3, the simulated runoff volume is significantly higher than that of the observed. On the other hand, the event CS4 cannot be improved any further. Increasing DS_i will improve the start time of the hydrograph, but also reduce the peak of event CS4. The 'best' impervious area parameter set of DCIA and DS_i obtained from hydrograph modelling also matched well with the values obtained from the RR plot (i.e. figure 5), which were 19% and 0.26 mm, respectively. As stated earlier, DCIA was also estimated from aerial photos and found to be 24% for the catchment. However, the values obtained from aerial photos include both directly connected impervious areas and supplementary areas. Therefore, it can be said that the calibrated value of DCIA matched well with the information obtained from the aerial photos and the RR plot.

The parameter values of DCIA and DS_i obtained from Stage 1 optimization were kept constant during Stage 2 calibration, and the parameters DS_p and CN were optimized. The initial (or seed) values for DS_p and CN were taken as the middle value of the range given in the ILSAX manual. The recommended range of DS_p in the ILSAX manual is between 2 and 10 mm, while the range of CN is between 1 and 4. The AMC of each calibration event was estimated using the 5-day rainfall totals prior to the events, using the information given in the ILSAX manual. Like in Stage 1, the numerical experiments conducted with different seeds showed that the optimized pervious area parameters obtained were the same under different seeds. The optimized pervious area parameters (i.e. DS_p and CN) corresponding to three 'large' storm events are given in table 5.

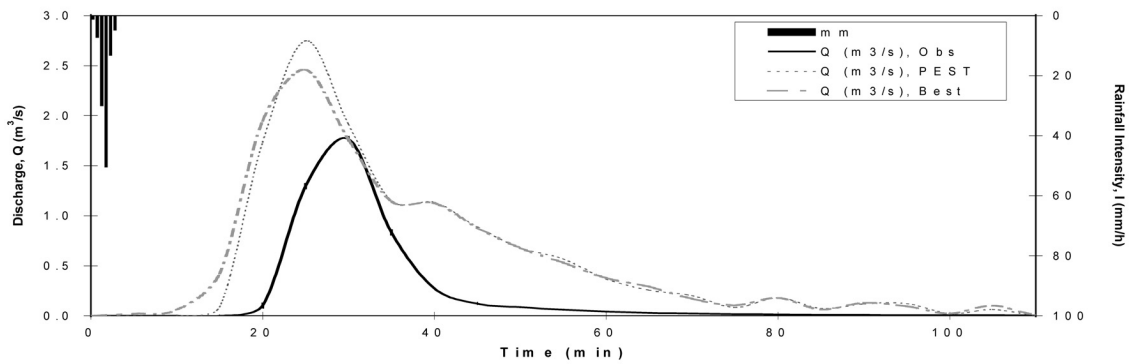
As in Stage 1 optimization, the 'best' parameter set for DS_p and CN was obtained from the outer optimization and found to be the parameter set corresponding to event CL3. The calibration plots of the three 'large' storm events are shown in figure 8, similar to 'small' events. Table 4 shows the comparison of peak discharge and runoff volume of observed and modelled (using the 'best' parameter set) hydrographs of these events. All these events had multi-peaks, and the calibration showed that the shape and time to peak were satisfactorily modelled for the three events. The AMC was not optimized for each storm event through PEST, but estimated from prior 5-day rainfall totals as recommended in the ILSAX manual. Nonetheless, the start



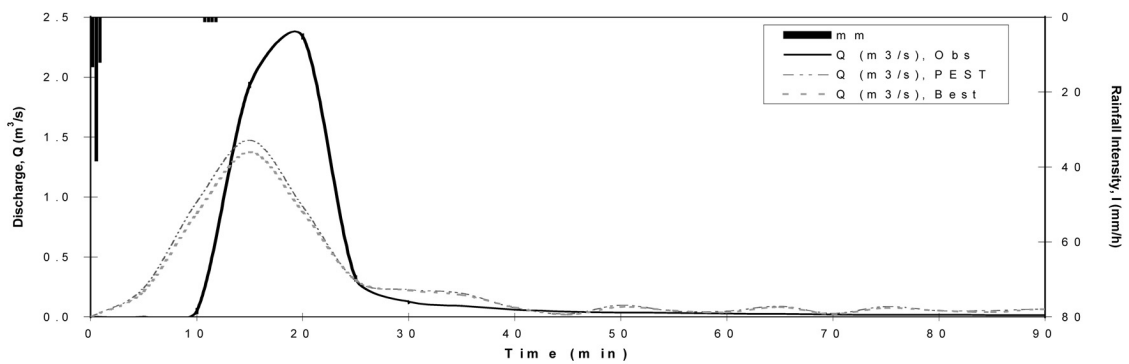
(a) Event CS1



(b) Event CS2



(c) Event CS3



(d) Event CS4

Figure 7. Calibration plots for 'small' storm events of Giralang catchment.

time of the computed hydrographs matched well with those of the observed. Moreover, this AMC estimation procedure reduced the number of parameters in PEST optimization, which in turn improved the efficiency of the convergence of PEST optimization.

7. Validation of model parameters

The model validation was done to test the performance of the calibrated model parameters on independent storm events which were not used in the calibration. As stated in section 4, two storm events were selected to validate the model parameters. The ILSAX model was run for these two events, with the 'best' set of parameters obtained from calibration (i.e. DCIA, DS_i, DS_p and CN). As for the calibration events, the AMC of each validation event was estimated using the 5-day rainfall totals prior to the events, using the information given in the ILSAX manual. The simulated hydrographs of the two validation events are shown in figure 9, together with the observed hydrographs. As for calibration events, table 4 shows the comparison of peak discharge and runoff volume of observed and modelled (using the 'best' parameter set) hydrographs of these events. These two events had multi-peaks, and the validation showed that the shape of hydrograph and the time to peak were satisfactorily modelled for both events with the 'best' parameter set. The peaks were underestimated slightly. However, in general, the validation seems to be good.

Table 3. Impervious area calibration parameters values.

Event	DCIA (%)	DS _i (mm)
CS1	20	0.6
CS2 *	19	0.0
CS3	24	2.0
CS4	21	0.0

* 'Best' parameter set from outer optimization.

Table 4. Observed and modelled peak discharge and runoff volume for calibration and validation events.

Event	Peak discharge (m ³ /s)		Runoff volume (mm)	
	Observed	Modelled	Observed	Modelled
CS1	1.441	1.391	2.7	3.0
CS2	0.725	0.607	1.1	1.1
CS3	1.767	2.459	1.6	4.0
CS4	2.339	1.374	1.8	1.6
CL1	7.123	4.690	28.4	25.0
CL2	4.980	9.000	13.2	22.8
CL3	6.206	3.413	9.9	7.6
V1	4.646	3.363	9.9	9.0
V2	2.806	1.267	12.9	7.8

8. Summary and conclusions

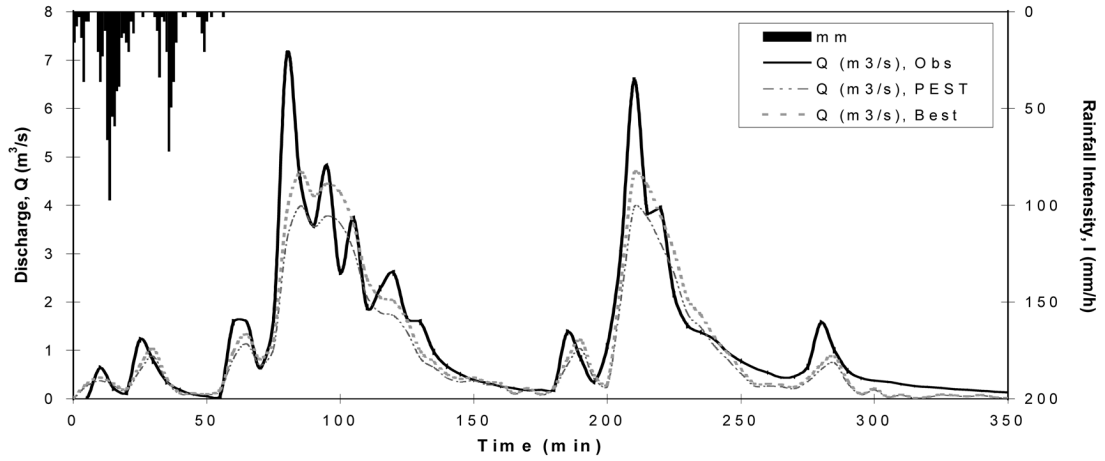
An optimization strategy, called two-stage inner/outer optimization, was developed in this study to calibrate the model parameters of urban drainage models, using hydrograph modelling. The ILSAX model was used, and the model parameters related to pervious and impervious areas were estimated. The parameter optimization was carried out in two stages. During Stage 1, the model parameters responsible for 'small' storm events (i.e. impervious area parameters of DCIA and DS_i) were obtained. During Stage 2, the additional parameters responsible for 'large' storm events (i.e. pervious area parameters of DS_p and CN) were obtained. During Stage 2, no changes were made to the parameters obtained from Stage 1. Each stage consisted of two loops (i.e. inner and outer). The inner loop uses the PEST computer software to optimize the model parameters corresponding to each storm event. The outer loop optimizes the above sets of model parameters to produce the 'best' set considering all calibration events and hydrograph attributes of runoff volume, peak discharge and time to peak. The outer optimization was carried out manually.

The Giralang catchment in Canberra (Australia) was considered in this study to demonstrate the calibration procedure. Four 'small' and three 'large' storm events were considered, and the model parameters DS_i, DCIA, DS_p and CN were optimized. The parameters DCIA and DS_i obtained through calibration were compared against the values obtained from rainfall and runoff depth plots of 'small' storm events and aerial photographs, and found to be satisfactory. The 'best' set of model parameters obtained from the two-stage inner/outer optimization was validated using two independent events, which were not used in calibration. The validation plots showed that the modelled hydrographs were similar to the observed hydrographs. The calibration and validation results showed that the two-stage inner/outer optimization strategy could be used to determine the model parameters of the ILSAX model of the Giralang catchment. Given the generic nature of the strategy, the procedure can be used for any urban drainage catchment modelled with any urban drainage computer modelling software.

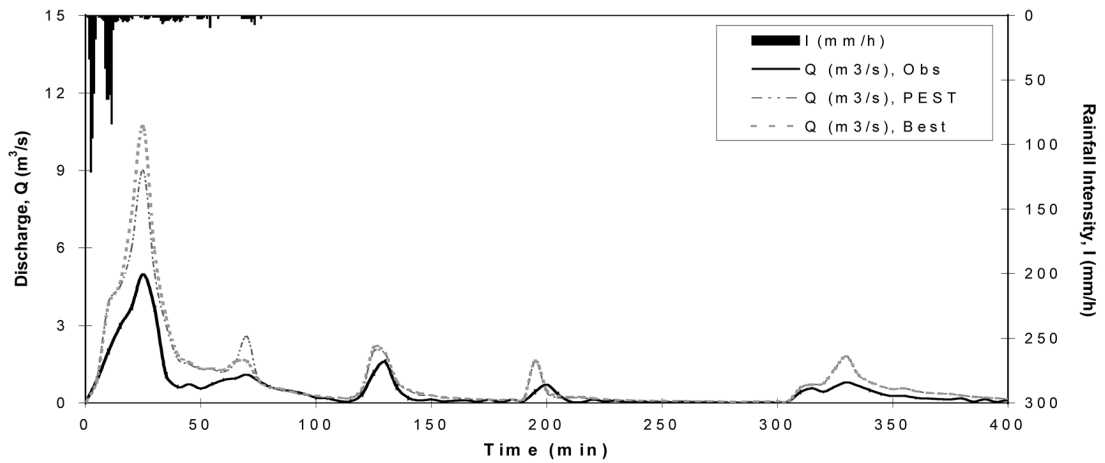
Table 5. Pervious area calibration parameters values.

Event	DS _p (mm)	CN
CL1	7.9	2.3
CL2	2.3	1.5
CL3 *	2.0	1.0

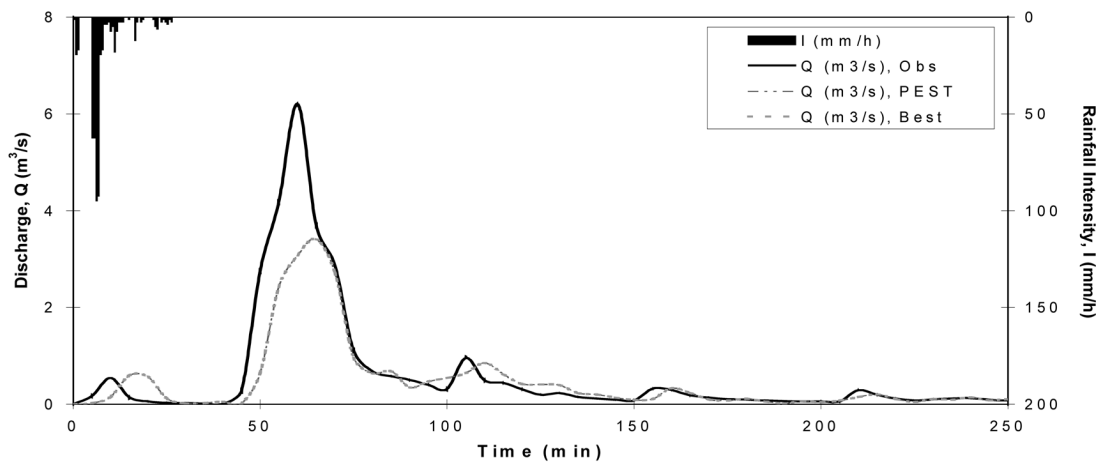
* 'Best' parameter set from outer optimization.



(a) Event CL1



(b) Event CL2



(c) Event CL3

Figure 8. Calibration plots for 'large' storm events of Giralang catchment.

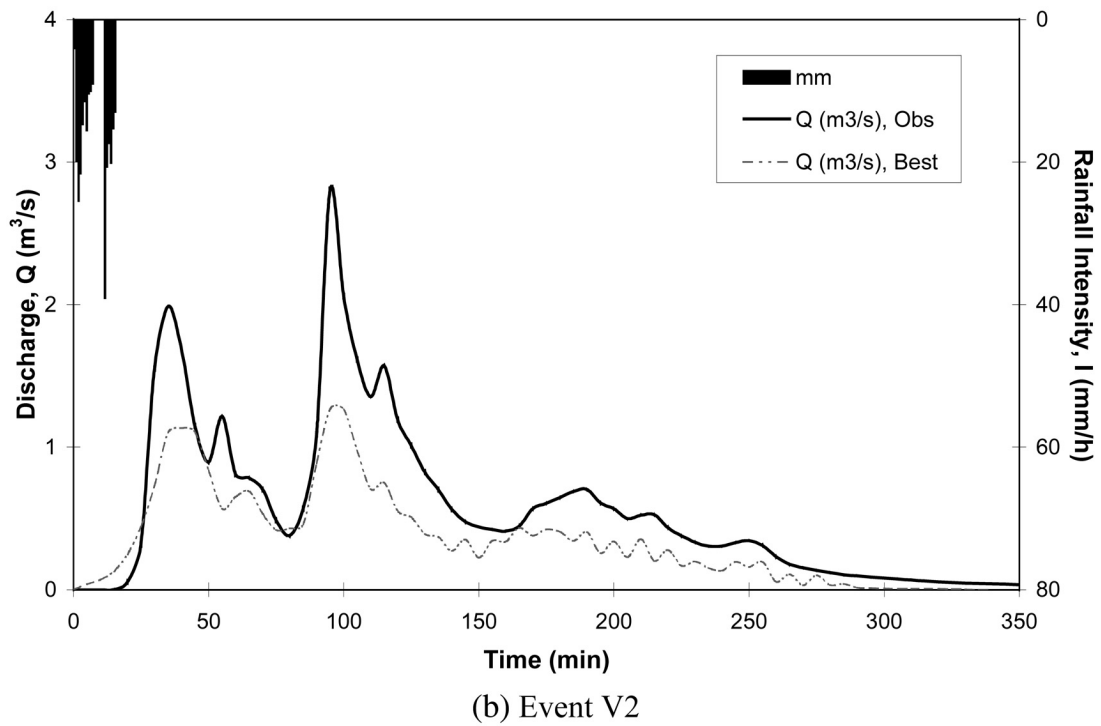
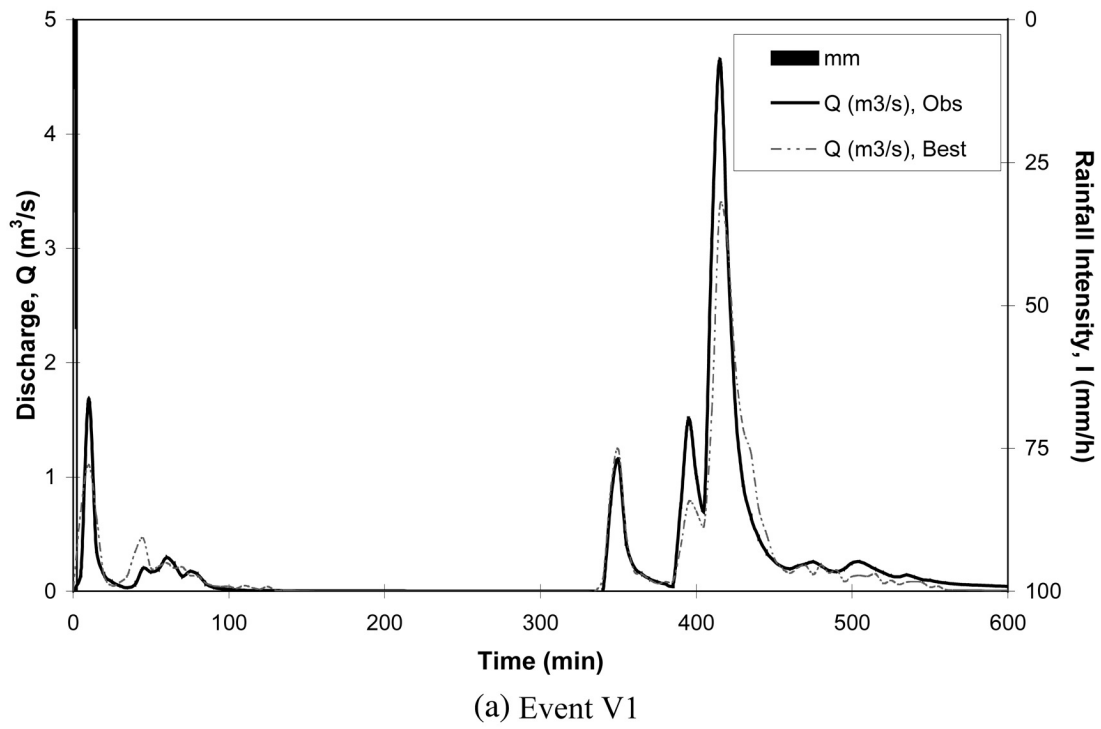


Figure 9. Validation plots for Giralang catchment.

References

- Bedient, P.B. and Huber, W.C., *Urban Hydrology, Hydrology and Floodplain Analysis*, 1992 (Addison-Wesley: New York).
- Boyd, M.J., Bufill, M.C. and Knee, R.M., Pervious and impervious runoff in urban catchments. *Hydrol. Sci. J.*, 1993, **38**, 463–478.
- Bufill, M.C. and Boyd, M.J., A simple flood hydrograph model for urban catchments, in *Proceedings of the International Symposium on Urban Stormwater Management*, 1992, pp. 98–103.
- Choi, K. and Ball, J.E., Estimation of control parameters for urban runoff modelling by using a hydroinformative system, in *Proceedings of the 8th International Conference on Urban Storm Drainage*, 1999, pp. 1776–1783.
- Chow, V.T., *Handbook of Applied Hydrology*, 1964 (McGraw-Hill: New York).
- Danish Hydraulic Institute, *Modelling of Urban Sewer Systems on Microcomputers, MOUSE V3.0, Users' Guide and Technical Reference*, 1988.
- Dayaratne, S.T., Modelling of urban drainage systems using ILSAX. PhD thesis, Victoria University, 2000.
- Dayaratne, T.S., Assessment of errors in commonly used event hydrograph urban catchment models. Masters thesis, University of Melbourne, 1996.
- Ghafouri, R.A., Deterministic analysis and simulation of runoff in urban catchments. PhD thesis, University of Wollongong, 1996.
- Heeps, D.P. and Mein, R.G., Independent comparison of three urban runoff models. *ASCE J. Hydraulics Div.*, 1973, **100**, 995–1009.
- Hill, M.C., *A Computer Program (MODFLOWP) for Estimating Parameters of a Transient, Three-Dimensional Groundwater Flow Model using Nonlinear Regression*, US Geological Survey Open-File Report, pp. 91–484, 1992.
- Johnston, P.R. and Pilgrim, D.H., Parameter optimization for watershed models. *Wat. Resources Res.*, 1976, **12**, 477–486.
- Kidd, C.H.R., Rainfall-runoff processes over urban surfaces, in *Proceedings of an International Workshop*, Report No. 53, 1978 (Institute of Hydrology: Wallingford, UK).
- Maheepala, U.K., Data acquisition and modelling of urban drainage catchment in the city of Knox. Masters thesis, Monash University, 1999.
- Maheepala, U.K., Takyi, A.K. and Perera, B.J.C., Hydrological data monitoring for urban stormwater drainage systems. *J. Hydrol.*, 2001, **245**, 32–47.
- Marquardt, D.W., An algorithm for least-squares estimation of nonlinear parameters. *J. Social Ind. appl. Math.*, 1963, **11**, 431–441.
- Muncaster, S.H., Weinmann, P.E. and Mein, R.G., An application of continuous hydrologic modelling to design flood estimation, in *Proceedings of the 24th Hydrology and Water Resources Symposium*, 1997, pp. 77–82.
- O'Loughlin, G., *The ILSAX Program for Urban Storm Water Drainage and Analysis. User's Manual for Microcomputer, Version 2.13*, 1993 (University of Technology: Sydney).
- O'Loughlin, G., Stack, B. and Wilkinson, A., Effects of varying time steps in urban rainfall-runoff models, in *Proceedings of the International Symposium on Stormwater Management (HydraStorm'98)*, 1998, pp. 57–62.
- Soil Conservation Service, *Engineering Handbook*, 1968 (US Department of Agriculture: Washington, DC).
- Stephens, M.L. and Kuczera, G., Testing the time-area urban runoff model at the allotment scale, in *8th International Conference on Urban Storm Drainage*, 1999, pp. 1391–1398.
- The Institution of Engineers, Australia, *Australian Rainfall and Runoff: a Guide to Flood Estimation*, Vol. 1, edited by D. H. Pilgrim, 1987.
- Watermark Numerical Computing, Australia, *PEST (Model Independent Parameter Estimation), User's Manual*, 1998.
- Watson, M.D., *Time-Area Method of Flood Estimation for Small Catchments*, Report 7/81, 1981 (Hydrological Research Unit, University of the Witwatersrand: Johannesburg).
- Zaman, S. and Ball, J.E., Simulation of small events in an urban catchment, in *Water Down Under' 94*, 1994, pp. 353–358.