Predicting pervious and impervious storm runoff from urban drainage basins

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Abstract Rainfall and runoff depths were analysed for 47 storms recorded on three urban drainage basins in Canberra, Australia. Three runoff mechanisms have been identified: runoff generated on effective impervious surfaces in all storms; runoff from pervious areas of small storage capacity during both large and small storms; and runoff from pervious areas of large storage capacity for larger storms. The data indicate that pervious surface runoff is generated on only a small part of the total basin area.

Prédiction des écoulements afférents à des averses sur les surfaces perméables et imperméables de bassins hydrographiques urbains

Résumé Cette étude est consacrée à l'analyse des précipitations et des écoulements relatifs à 47 averses sur trois bassins hydrographiques urbains de la ville de Canberra (Australie). Les trois mécanismes d'écoulement identifiés sont: l'écoulement produit par des surfaces effectivement imperméables pour l'ensemble des averses; l'écoulement produit par des surfaces perméables à faible capacité d'emmagasinement pour les petites averses et les averses importantes; et enfin l'écoulement produit par des surfaces perméables à forte capacité d'emmagasinement pour les averses importantes. Les données montrent que la surface perméable génératrice d'écoulements ne représente qu'une faible proportion de la surface totale du bassin.

INTRODUCTION

In urban drainage basins, storm runoff is generated on impervious surfaces such as roads and roofs, and it may also be generated on pervious surfaces if antecedent wetness is high or if rainfall intensities or total rainfall depths are large. In many countries pervious surface runoff is only a small part of urban stormwater runoff, but in Australia pervious runoff is significant in terms of both the percentage of events and the contribution to total runoff depth.

Analysis of recorded rainfall and runoff depths can be used to indicate

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the relative contributions of pervious and impervious areas to total runoff, and this paper describes one such study.

DETAILS OF DRAINAGE BASINS AND STORMS

Tables 1 and 2 give details of the urban basins and storm events involved in the study. The basins are located in the city of Canberra, ACT, Australia, and the data collecting authority is ACT Electricity and Water. The basins are adjacent to one another, with LGC and MAW forming the major tributaries of the larger CUR basin (Fig. 1). Land use is predominantly single family residential, with some commercial development and large areas of parkland. The urban fraction of LGC is small and has no designated parkland. By contrast, close to one third of the urban fraction in MAW and CUR drainage basins is made up of parkland, and this is included with natural parkland in the land use column of Table 1. All streets have kerbs and gutters, and roofwater is connected into the piped drainage system. The drainage system on each basin flows into a creek which has been upgraded to a lined and grassed drainage channel. Soil type is medium clay, and the parkland is mainly native grass cover with scattered trees. Equal area main stream slopes are 0.035, 0.034 and 0.021 for LGC, MAW and CUR respectively.

***Table 1** Details of drainage basins*

Basin	Code	Area (km^2)	Urban fraction	Mapped impervious fraction	Land use %	Effective impervious fraction, F_i
Long Gully Ck at Phillip	LGC	5.02	0.16	0.05	Park 84 Resdtl 16	0.059
Yarralumla Ck at Mawson	MAW	4.45	0.86	0.26	Park 43 Resdtl 57	0.208
Yarralumla Ck at Curtin	CUR	26.90	0.57	0.17	Park 61 Resdtl 39	0.174

***Table 2** Details of storms*

Basin	Number of events	Rainfall range (mm)	Runoff range (mm)	Impervious events	Pervious events
LGC	43	2.5 – 138	0.4 –37	20	23
MAW	44	5.3 – 139	1.0 – 76	23	21
CUR	47	3.5 – 138	0.9 – 64	23	24

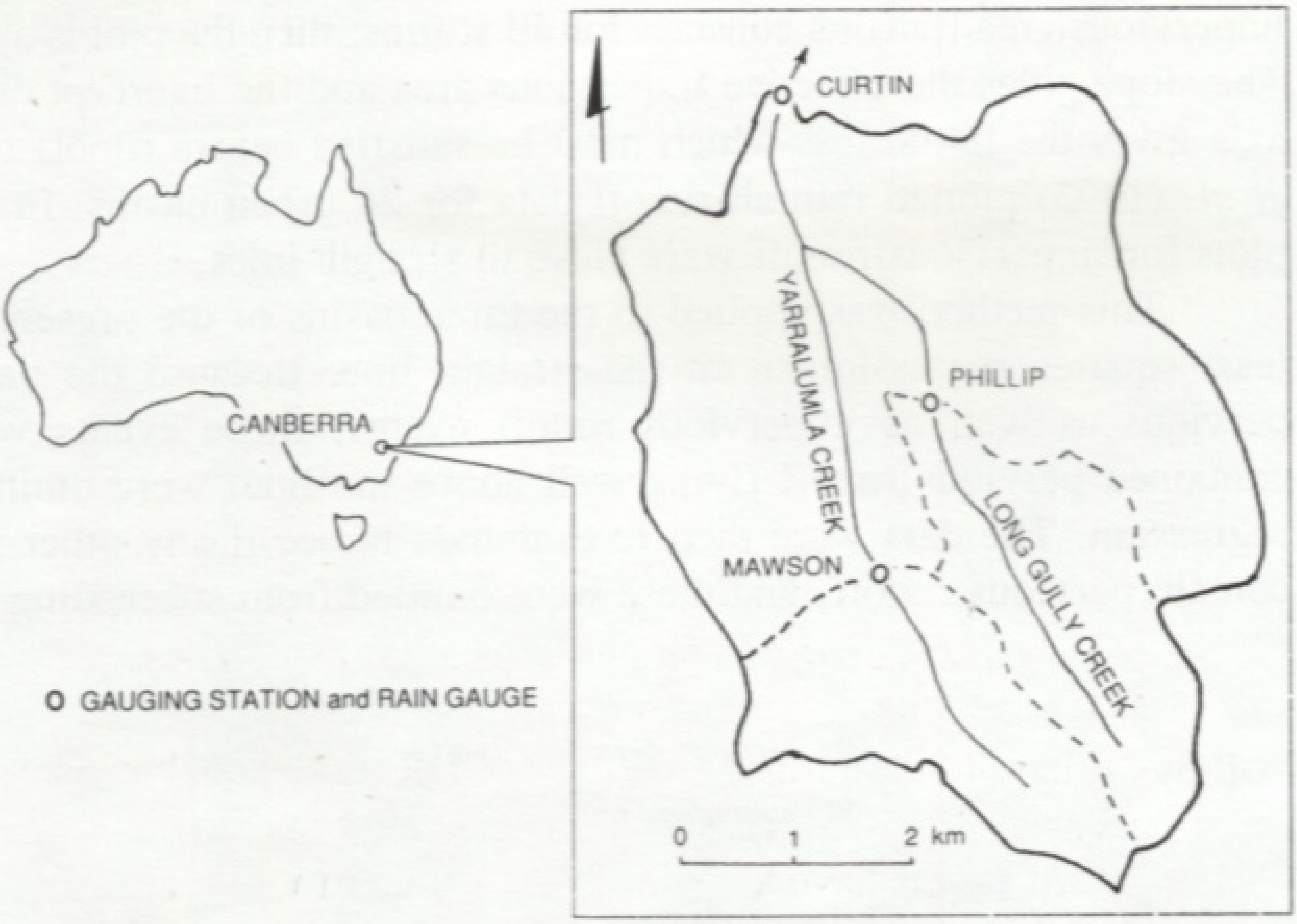

***Fig. 1** Urban drainage basins.*

Average annual rainfall and pan evaporation are 625 and 1710 mm respectively. Rainfall occurs fairly uniformly throughout the year, but is slightly higher in the warmer months from October through to May, often associated with thunderstorms, and 42 of the 47 storms occurred in this period.

Three raingauges were used, with the storm rainfall hyetograph for each basin taken from the nearest raingauge. Daily rainfall totals were also extracted from the data, to calculate antecedent wetness of the basins. These daily rainfalls were taken from one raingauge located centrally to all three basins.

These basins were included in a previous study by Boyd *et al.*(1993) and additional events were added for this more detailed examination of pervious area runoff.

IDENTIFYING PERVIOUS AND IMPERVIOUS AREA RUNOFF

In urban basins, runoff comes from the impervious surfaces which are directly connected to the drainage system, often called the effective impervious area. In some storms runoff may also come from pervious surfaces, or from impervious surfaces which are not directly connected and where part of the flow path is over pervious surfaces. The total storm runoff therefore can be considered to consist of an impervious contribution which is present for all storms, plus a contribution which is sometimes present depending on the condition of the pervious surfaces.

The effective impervious area can be identified by plotting total storm rainfall depth P against runoff depth Q, as for example in Miller (1978), Jacobsen & Harremoes (1981) and Pratt *et al.* (1984). If the effective impervious area remains constant for all storms, then the plot is a straight line. The slope gives the effective impervious area and the intercept on the rainfall axis gives the initial loss which must be satisfied before runoff occurs. Boyd *et al.* (1993) plotted rainfall-runoff data for 26 urban basins. In all cases the plots for impervious runoff were close to straight lines.

This method was applied to the three basins of the present study using least squares regression to fit the straight line. Because the data contained pervious as well as impervious runoff events, those events which clearly contained pervious runoff (lying well above the line) were omitted from the regression. The data were then re-examined to see if any other points might contain pervious runoff, and these were omitted from succeeding regressions.

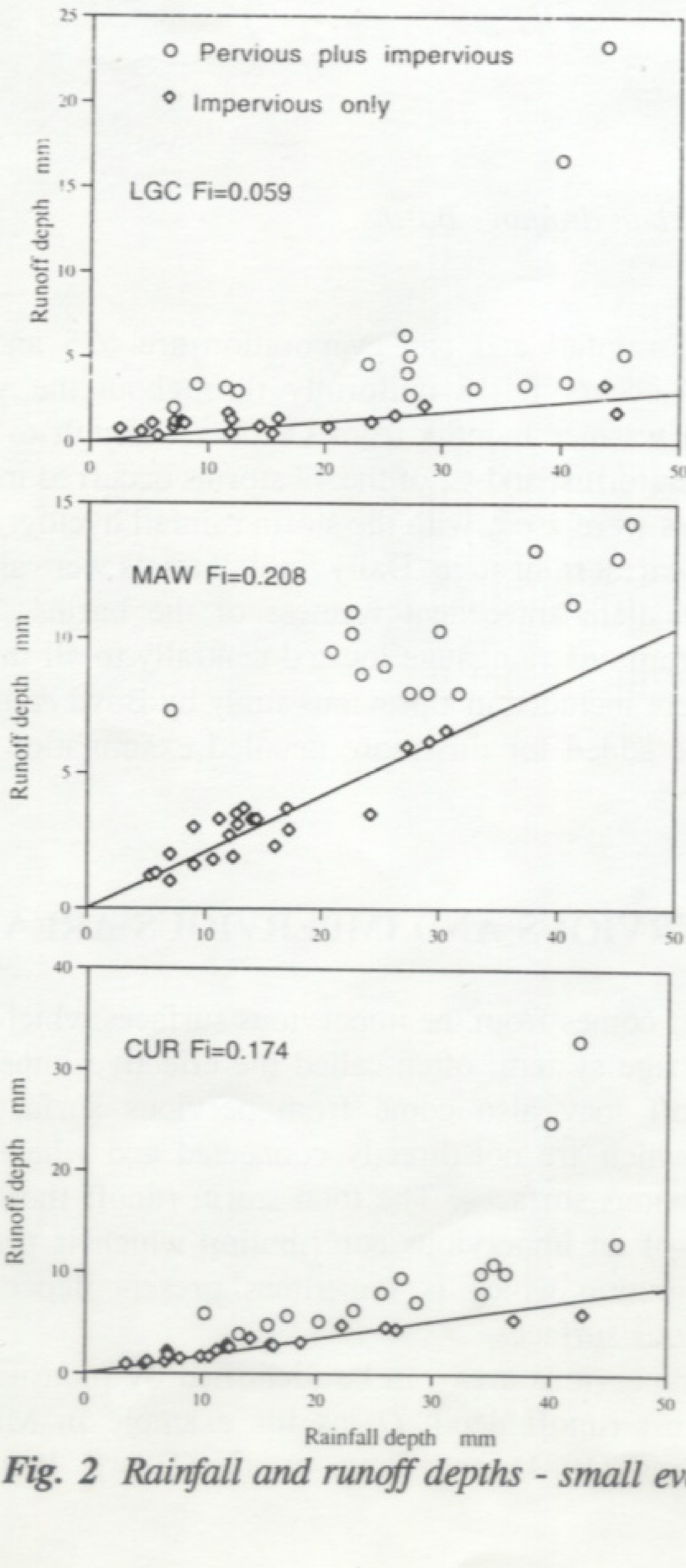

Fig. 2 Rainfall and runoff depths - small events.

The criterion adopted for omitting such events was that the deviation above the line exceeded 1 mm. As a comparison, the standard error of estimate of all impervious runoff events about the fitted line was 0.66, 0.66 and 0.57 mm for LGC, MAW and CUR basins respectively. Plots of the smaller events were also used to help identify impervious runoff (Fig. 2). Separation of impervious runoff events from other events was relatively straightforward for MAW and CUR basins, but less so on LGC where four events were doubtful. Examination of indices of basin antecedent wetness, however, revealed that these events were more consistent with the group of events containing pervious area runoff, and so they were included in that group. Table 1 gives values of the effective impervious area fraction calculated in this way and Fig. 3 shows the plotted

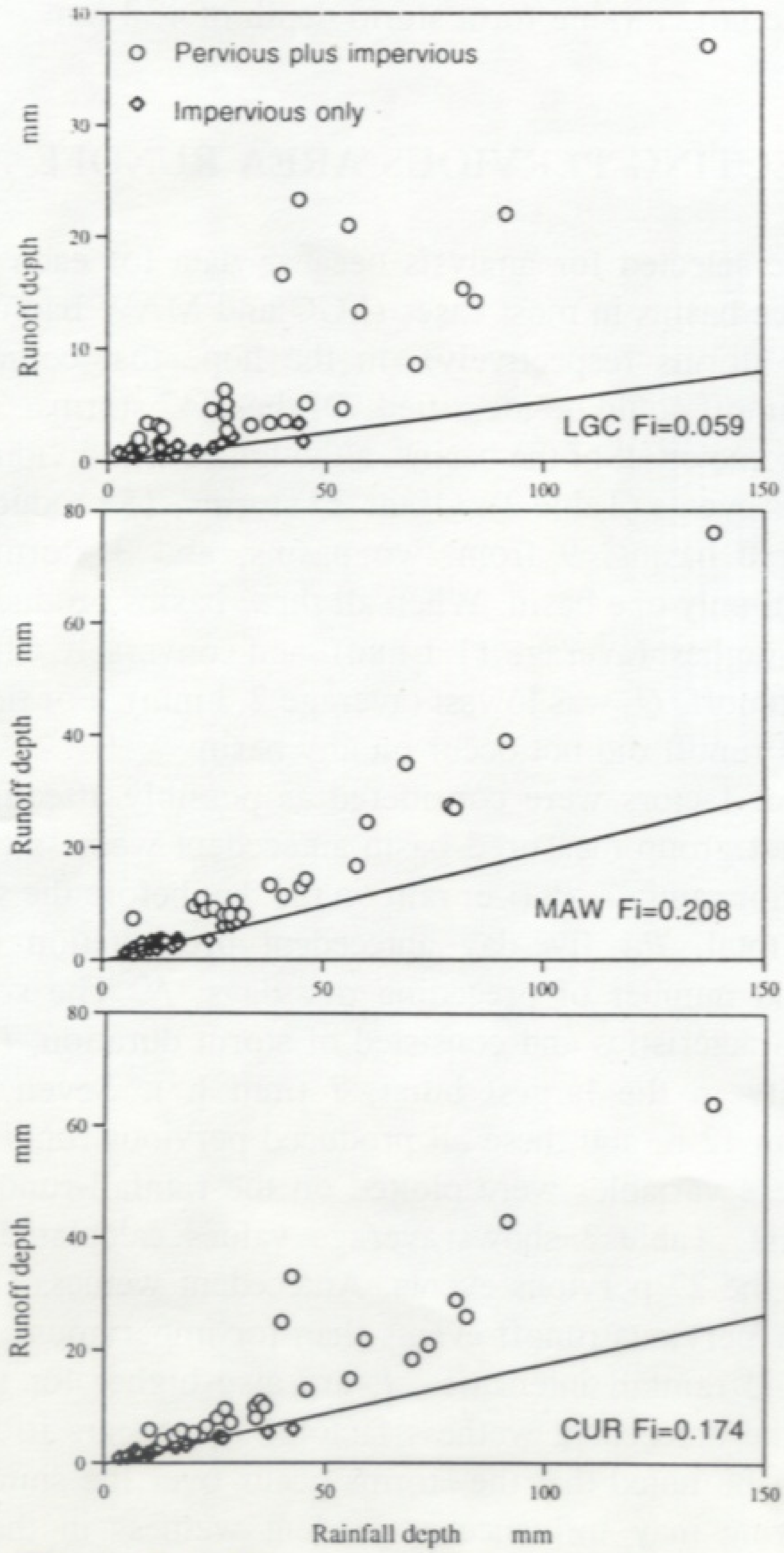

Fig. 3 Rainfall and runoff depths - all events.

data for all events. Because impervious areas, including roofs, are well connected to the drainage system in these basins, initial losses were found to be very close to zero.

Australian basins have been found to have considerably more pervious area runoff compared to basins in many other countries (Boyd *et al.*, 1993). The effective impervious area fraction, F_i, calculated from the regressions was used to calculate the impervious runoff, Q_i, in each event, and the pervious runoff, Q_p, could then be estimated by subtraction from the total runoff depth, Q:

$$Q = Q_i + Q_p = P.F_i + Q_p \tag{1}$$

Pervious runoff contributions to total runoff calculated in this way ranged from 1 mm to 47 mm, the larger value for a storm depth of 138 mm.

FACTORS AFFECTING PERVIOUS AREA RUNOFF

The 47 storms were selected for analysis because data for each storm were available for all three basins in most cases (LGC and MAW had missing data for four and three storms respectively), in the hope that common factors affecting pervious runoff could be identified. Of these 47 storms, 27 produced pervious runoff on some or all of the basins, although each individual basin had less than 27 pervious events (Table 2). Of the 27 storms, 15 produced pervious runoff from all three basins, 9 from two basins, and 3 storms produced pervious runoff from only one basin. When all three basins produced pervious area runoff, Q_p was highest (average 11.1 mm), and conversely when only one basin had pervious runoff, Q_p was lowest (average 2.3 mm). For the remaining 20 storms, pervious runoff did not occur on any basin.

Two groups of factors were considered as possibly affecting pervious area runoff. The first group measured basin antecedent wetness (in mm) and included one-day prior rainfall, P_1 (i.e. rain on the day before the storm); five-day prior rainfall total, P_5; five-day antecedent precipitation index (with $K = 0.9$), API_5; and number of preceding dry days, N. The second group measured storm characteristics and consisted of storm duration, D (minutes), and rainfall intensity in the largest burst, I (mm h^{-1}). Seven storms had durations longer than 12 h, and these all produced pervious runoff.

Values of these variables were plotted on the rainfall-runoff plots and trends were apparent. Table 3 shows average values calculated for the 20 impervious and for the 27 pervious events. Antecedent wetness (P_1, P_5, API_5 and N) is higher for pervious runoff events than for impervious events. Total storm depths, P, and rainfall intensities, I, are also higher for the pervious runoff events. Of the antecedent wetness factors, P_1 appears to be the most significant. It might be noted that the storms occur over the summer months when garden watering may influence antecedent wetness in the residential areas, particularly if several dry days occur. Thus P_1, P_5, API_5 and N may not reflect the true antecedent wetness of the basins. However this does not affect the extensive areas of parkland. Total rainfall depth, *P*, and intensity, *I*, also appear to be significant. Mean storm duration, *D*, was skewed by the presence of a few very long duration pervious storms and median durations of 70 and 120 min respectively, for impervious and pervious storms, were calculated.

***Table 3** Average values of factors affecting pervious runoff*

	Number of storms	P_1 mm	P_5 mm	API_5 mm	N days	D min	I mm h^{-1}	P mm
All basins:								
Impervious runoff only	20	0.5	8.2	5.8	3.8	70	14.5	14.2
Impervious + pervious runoff	27	3.8	12.5	9.6	2.0	120	32.6	42.8
Rainfall < 40 mm:								
LGC Imp	20	0.3	8.1	5.7	5.2	93	16.3	14.5
LGC Per	14	2.5	10.8	8.0	1.6	214	36.5	27.3
MAW Imp	23	1.2	8.5	6.1	3.5	72	15.4	15.8
MAW Per	14	2.3	10.3	7.6	2.2	78	38.6	29.3
CUR Imp	23	0.6	7.3	5.2	4.0	60	17.9	16.8
CUR Per	14	3.3	12.3	9.1	1.3	83	34.5	25.3

By examining events with less than about 40 mm rainfall (Fig. 2), it is apparent that the data consist of two groups, *viz.* a lower group of impervious runoff events, plus a group of combined pervious plus impervious runoff events which lie approximately 2 to 5 mm above the impervious events. Table 3 gives average values of antecedent wetness and storm characteristics for these groups on each of the three basins. In all cases antecedent wetness is greater for the events containing pervious runoff than for the impervious runoff events. Storm durations are slightly longer and rainfall intensities greater for the pervious events.

It is thus clear that three mechanisms are acting. For smaller events, runoff is generated only on impervious surfaces if the antecedent wetness is low, and on both pervious and impervious surfaces if the antecedent wetness is high. Evidently the pervious area soil store must be full or part-full to generate runoff. Additionally, large amounts of runoff are generated on pervious surfaces for the very large storms. In this case the large rainfall depth is sufficient to fill the soil store.

PREDICTING STORM RUNOFF

Prediction equations were developed for three cases: runoff from effective impervious surfaces; small amounts of pervious area runoff (using storms with less than about 40 mm rainfall depth); and large amounts of pervious area runoff from storms greater than 40 mm depth.

For runoff from effective impervious surfaces, a least squares linear regression was fitted to the data points. The criterion for omitting pervious runoff events from the regressions has been discussed previously. The resulting relation was :

$$Q_i = F_i.P \tag{2}$$

Values of F_i are given in Tables 1 and 4, and are close to the mapped impervious fraction for two basins, and somewhat less for the third. This is consistent with a study of 26 urban basins, (Boyd *et al.*, 1993) in which the effective impervious fraction determined from rainfall and streamflow data was, on average, slightly less than the directly connected impervious fraction estimated from maps.

Table 4 *Parameters of conceptual urban runoff model*

Method	Basin	Impervious	Small pervious			Large pervious		
		F_i	F_{ps}	S_{ps}	a	F_{pl}	S_{pl}	b
Multiple regression	LGC	0.059	0.013	−54.1	6.2	0.102	0.5	3.8
	MAW	0.208	0.087	3.5	1.2	0.236	48	1.9
	CUR	0.174	0.043	−6.1	1.8	0.168	19	2.1
Constrained optimization	LGC	0.059	0.095	0	1.0	0.104	34	2.0
	MAW	0.208	0.090	4.0	1.0	0.230	49	2.0
	CUR	0.174	0.055	0.7	1.0	0.185	31	2.0

For storms with rainfalls less than about 40 mm, small quantities of pervious runoff were generated if the basin antecedent wetness or rainfall intensity was high (Table 3). Simple regressions and multiple regressions between total runoff, Q, for these events and the antecedent and storm variables listed in Table 3 were examined.

The most significant variables were found to be P followed by P_1. The next most significant were P_5 and API_5, while the other variables N, D and I were not generally significant (0.01 level). Variables P and P_1 were also found to be consistent (i.e. positive correlation) for all three basins, whereas P_5 and API_5 sometimes exhibited negative correlation and predicted a decrease in runoff for an increase in antecedent wetness. The best regressions were:

$$\text{LGC} \quad Q = 0.725 + 0.0724 \times P + 0.0836 \times P_1 \qquad N = 34 \quad r^2 = 0.429 \tag{3a}$$

$$\text{MAW} \quad Q = -0.308 + 0.295 \times P + 0.105 \times P_1 \qquad N = 37 \qquad r^2 = 0.755 \tag{3b}$$

$$\text{CUR} \quad Q = 0.264 + 0.217 \times P + 0.0796 \times P_1 \qquad N = 37 \qquad r^2 = 0.712 \tag{3c}$$

A similar procedure was applied to the larger pervious runoff events, i.e. those when P exceeded 40 mm. The smaller number of events limited the use of multiple regression, and this was restricted to the use of P plus one other independent variable. The best variables were found to be P_5 and API_5, with API_5 slightly better. P_1 did not give consistent results, predicting less runoff for wetter antecedent conditions. The adopted equations were:

$$\text{LGC} \quad Q = 0.675 + 0.174 \times P + 0.386 \times API_5 \qquad N = 9 \qquad r^2 = 0.872 \tag{4a}$$

$$\text{MAW} \quad Q = -11.60 + 0.531 \times P + 0.441 \times API_5 \qquad N = 7 \qquad r^2 = 0.937 \tag{4b}$$

$$\text{CUR} \quad Q = -3.02 + 0.385 \times P + 0.349 \times API_5 \qquad N = 10 \qquad r^2 = 0.748 \tag{4c}$$

A MODEL FOR PERVIOUS AND IMPERVIOUS AREA RUNOFF ON URBAN DRAINAGE BASINS

The plots in Figs 2 and 3 and the regressions of the previous section indicate that three mechanisms are acting to generate runoff from these basins:

(a) runoff from effective impervious surfaces such as roads and roofs which are directly connected to the stormwater drainage system. Initial losses are small, F_i is consistent over a wide range of storm sizes and is approximately equal to or slightly less than the mapped impervious fraction;

(b) small amounts of runoff (2 to 5 mm) from pervious surfaces, probably located close to the drainage system. This runoff occurs for storm rainfall depths as low as 6 mm and is related to the one-day prior rainfall, P_1, indicating that the source may be a soil store of small capacity which depletes rapidly after the storm ends. A model for this is shown in Fig. 4. The runoff from effective impervious surfaces, plus these pervious surfaces is :

$$Q = Q_i + Q_{ps} = F_i.P + F_{ps}(P - S_{ps} + aP_1) \tag{5}$$

Using the values of F_i from Table 4, comparison of equations (3) and (5) allows values of the small pervious area fraction, F_{ps}, soil store capacity, S_{ps}, and weighting factor, a, to be estimated (Table 4); and

(c) larger amounts of runoff from pervious areas, ranging from 5 to 47 mm, which occur during storms with rainfall depths greater than about

40 mm. This runoff is related to API_5, indicating a soil store of large capacity which takes some days to deplete. Figure 4 shows this part of the model. The equation for total runoff for the urban basin is then:

$$Q = Q_i + Q_{ps} + Q_{pl} = F_i.P + F_{ps}(P - S_{ps} + aP_1) + F_{pl}(P - S_{pl} + bAPI_5) \quad (6)$$

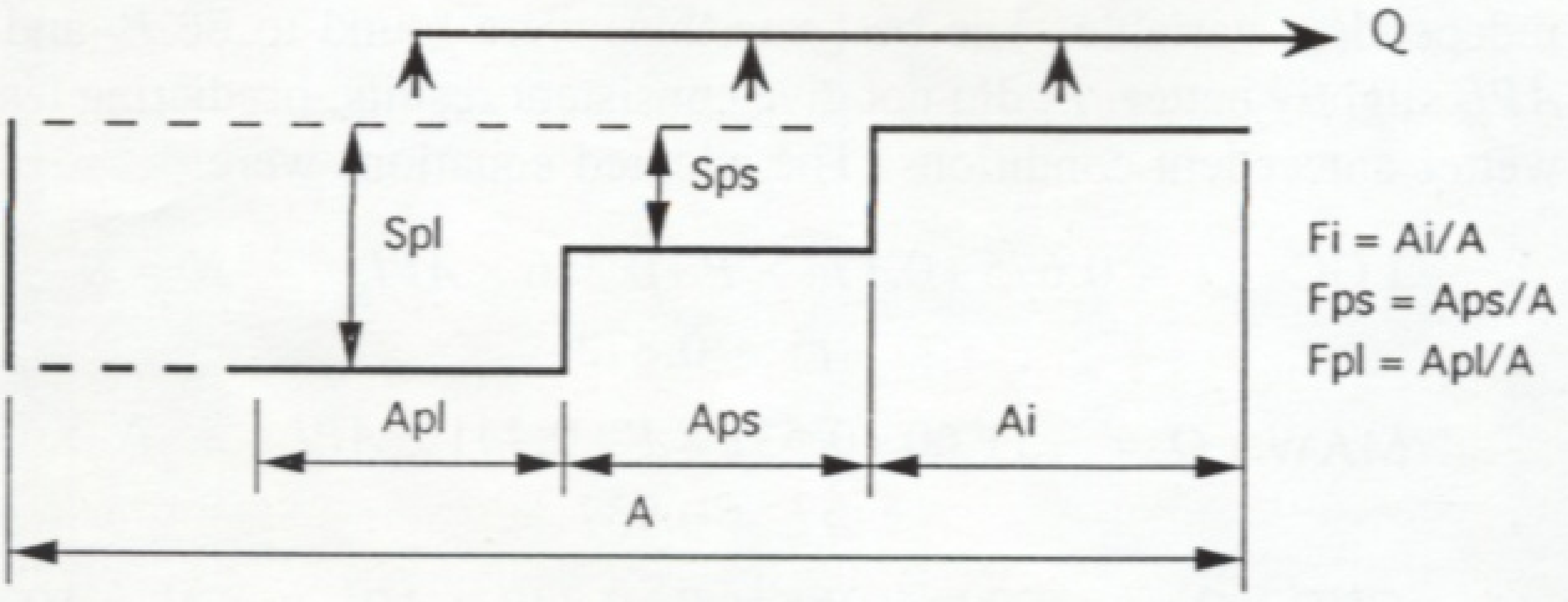

Fig. 4 Conceptual model of urban storm runoff depths.

Comparison of equations (4) and (6) allows values of F_{pl}, S_{pl} and b to be estimated (Table 4). Note that the term $F_{ps}.a.P_1$ is omitted in estimating these values, since the variable P_1 does not appear in equation (4); however this has only a small effect since values of $F_{ps}.a.P_1$ are typically only 0.3 mm.

The values in Table 4 generally support the conceptual model of Fig. 4. Each basin has an effective impervious area fraction, F_i, plus an area fraction, F_{ps} contributing small amounts of pervious runoff. This pervious soil store has a small capacity, S_{ps}, of a few mm. For larger storms, pervious runoff is generated from an additional area fraction F_{pl} which has a large capacity S_{pl} of between 30 and 50 mm. However some values in Table 4 are clearly incorrect, in particular the negative soil store capacities for the small pervious runoff events, and these in turn cause errors in estimation of the soil store capacities for the larger pervious runoff events.

To overcome these difficulties, the regressions can be constrained, or values of F_{ps}, S_{ps}, a, F_{pl}, S_{pl} and b can be determined by constrained optimization. Optimization was used and the first constraint applied was that soil store capacities, S_{ps} and S_{pl} must be greater than or equal to zero. When this was done, the weighting factors, a and b, were found to be close to 1.0 and 2.0 respectively on average, so the optimization was repeated with the additional constraints, $a = 1$, $b = 2$. The objective function (sum of deviations squared) changed by only a small amount, except for small pervious events on LGC.

Table 4 shows optimized values of the pervious fractions and soil store capacities. Comparing the ratio of explained/total variation, the constrained optimization results were only slightly worse than the multiple regression results for MAW and CUR basins, but somewhat worse for LGC. For LGC the explained/total variations reduced from 43% (equation (3a)) to 31% for the small pervious runoff events, and from 87% (equation (4a)) to 72% for the large pervious runoff events.

By summing values of F_i, F_{ps} and F_{pl} in Table 4, the data indicate that runoff is generated on only a part of these three catchments, the portion ranging from 26% on LGC to 53% on MAW. Although the role of source areas is well known, (Betson, 1964; Boughton, 1987), it was decided to check the result further by repeating the optimization with the constraint that $F_i + F_{ps} + F_{pl} = 1$. F_i and F_{ps} were set at the values in Table 4 and F_{pl} was adjusted. Results were considerably poorer, with the objective function increasing markedly and consequently the ratio of explained/total variation decreasing to 5%, 80% and 22% respectively for LGC, MAW and CUR. A check was also made to establish whether the size of the source areas varied with antecedent wetness, by expressing F_{pl} as a product of API_5 in the optimization. Similar poor results were obtained. Within the limitation of this small number of large pervious runoff events, the data indicate that pervious area runoff is generated on a fixed part of the basin which does not vary with antecedent wetness.

It should be noted that the values of Q_i, Q_{ps} and Q_{pl} in equations (2), (5) and (6) are depths of runoff averaged over the total basin, and that the actual depths generated on each surface are Q_i/F_i, Q_{ps}/F_{ps} and Q_{pl}/F_{pl} respectively. Thus, for example, the runoff amounts of from 2 to 5 mm from the small pervious areas result from much larger depths of runoff from these surfaces. Considering equation (6) and the optimized values in Table 4, since S_{ps} and P_1 are small, the actual depth of runoff from the small pervious surfaces is close to the rainfall depth, P (i.e. the soil store capacity is small). The actual runoff depth from the large pervious surfaces is equal to the rainfall depth less the soil moisture deficit ($S_{pl} - b.API_5$).

CONCLUSIONS

Analysis of recorded rainfall and runoff data from three urban basins in Canberra, Australia, revealed three distinct runoff mechanisms: runoff from effective impervious surfaces; runoff from pervious surfaces (ranging from 2 to 5 mm) from soil stores of small capacity for both small and large storms; and runoff from pervious surfaces of larger size when rainfall depths exceeded about 40 mm.

The effective impervious fraction was found to be close to the mapped impervious fraction. The first type of pervious runoff was found to be related to the one-day prior rainfall, suggesting that the runoff was generated from a surface store of small capacity which depletes rapidly after rainfall ends. The small size of this store was confirmed by multiple regression and constrained optimization analyses. Large pervious runoff depths were found to be related to five-day prior rainfall (*API_5*), suggesting that this runoff comes from a store of large capacity which depletes slowly. Regression and optimization analyses also confirmed the large size of this store.

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