Pervious and impervious runoff in urban catchments

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Abstract Rainfall and runoff depths were examined for 763 storms on 26 urban basins located in 12 countries. For 17 of the basins, impervious surfaces were the major contributors to storm runoff. These basins were generally smaller than 25 ha and had small to medium storms in the data set. Nine basins had significant amounts of runoff from pervious as well as impervious surfaces. Eight of these basins are located in Australia. For all 26 basins, plots of rainfall and runoff depths were used to estimate the effective impervious area and the impervious area initial loss. The data plotted close to a single straight line on all basins, indicating that the effective impervious area remained constant for all storm sizes. The effective impervious fraction was related to total impervious area and the directly connected impervious fraction estimated from maps. For the basins with pervious runoff, the depth of rain in the storm was the most important factor in determining pervious runoff for rainfalls less than 50 mm, while for larger storms other factors including rainfall intensity and antecedent wetness were also found to be significant.

Ecoulement d'averses sur des surfaces perméables et imperméables dans des bassins hydrographiques urbains

Résumé Cette étude est consacrée aux précipitations et aux écoulements relatifs à 763 averses observés sur 26 bassins hydrographiques urbains situés dans 12 pays différents. Pour 17 bassins, les surfaces imperméables apportent la majeure partie de l'écoulement; la superficie de ces bassins est généralement inférieure à 25 ha et les averses observées d'importance faible ou moyenne en comparaison de l'ensemble des données recueillies. Dans neuf bassins les surfaces perméables apportent, comme les surfaces imperméables, une contribution significative à l'écoulement; huit de ces bassins se trouvant en Australie. Pour l'ensemble des 26 bassins hydrographiques, les graphiques des précipitations et des écoulements ont permis d'estimer la surface imperméable efficace et la perte initiale de la surface imperméable. Le tracé des données pour chaque bassin est proche d'une ligne droite, indiquant que la surface imperméable efficace reste constante quelle que soit l'importance de l'averse. On a étudie les corrélations existant entre les surfaces imperméables efficaces estimées d'après les données et les surfaces imperméables totales d'une part, les surfaces imperméables drainées par les réseaux d'assainissement d'autre part, ces dernières surfaces étant estimées d'après les plans urbains. Pour les bassins à écoulement perméable, la hauteur de l'averse est le facteur principal de

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l'écoulement perméable pour les précipitations de moins de 50 mm, tandis que pour les averses plus importantes, d'autres facteurs, dont l'intensité pluviale et l'humidité antérieure du sol, se sont révélés importants.

INTRODUCTION

Knowledge of the contributions to urban stormwater runoff from pervious and impervious surfaces is useful for the hydraulic design of stormwater systems as well as for modelling non-point source pollution.

An urban basin can be broadly considered to be made up of three types of surface:

(a) impervious areas (A_{ic}) which are directly connected to the drainage system, typically roads, parking lots and in some cases roofs;

(b) additional impervious areas which are not directly connected, runoff from which flows over pervious surfaces before reaching the drainage system. Together (a) and (b) make up the total impervious area (A_i); and

(c) the remainder, pervious or semi-pervious area (A_p) consisting of lawns, gardens and parklands. The total basin area is then $A = A_i + A_p$.

On each surface, interception and depression storage must be satisfied before runoff commences and this storage forms an initial abstraction or initial loss from the rainfall hyetograph. Initial losses are known to be small on the impervious surfaces (Melanen & Laukkanen, 1981; Pratt *et al.*, 1984; Jensen, 1990), but larger on pervious areas. Continuing losses may also be significant on pervious surfaces.

Runoff from pervious surfaces is more difficult to predict than runoff from impervious surfaces because it depends on soil and vegetation type as well as on antecedent wetness. Also, the pervious part of a basin may contain source areas which generate most of the runoff with little runoff coming from the remaining pervious areas. If so, pervious area runoff will depend on the extent and location of the source areas. Source areas located close to the drainage system may be significant contributors to runoff while those located further away may contribute very little to the drainage system. Finally, pervious area runoff may depend on storm intensity and duration as well as on antecedent conditions. A good description of the factors affecting runoff from urban basins is given by Packman (1979).

Plots of runoff depth against rainfall depth (Fig. 1) have been used in many studies to determine the initial losses and sizes of the various types of surface (Miller, 1978; Miller *et al.*, 1978; Jacobsen & Harremoes, 1981; Pratt *et al.*, 1984; Bufill & Boyd, 1992). Points to note in Fig. 1 are:

(a) the runoff depth (Q) is equal to the runoff volume divided by the total basin area (A) i.e. it is the runoff volume averaged over the total basin;

(b) the slope of each segment gives the fraction of the basin which is contributing to runoff. Thus if all of the impervious connected area is contributing runoff, segment I has slope A_{ic}/A. In segment II, if all impervious surfaces are contributing, the slope is A_i/A. Similarly, segment III

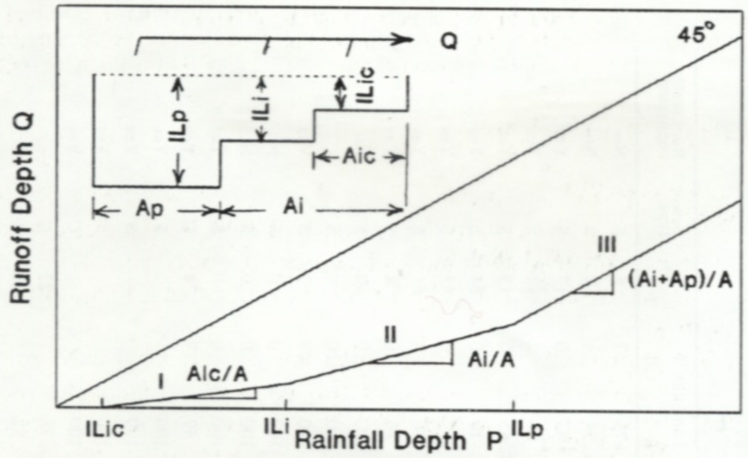

Fig. 1 Schematic rainfall-runoff relationship.

represents runoff from all the impervious areas plus that part of the pervious area (A_{pc}) contributing runoff, and has slope $(A_i + A_{pc})/A$. If all of the pervious area is contributing runoff, $A_{pc} = A_p$ and segment III has slope 1:1;

(c) each segment departs from the preceding one when the storm rainfall depth exceeds the corresponding initial loss for that surface; and

(d) if rainfall has occurred prior to an event then the soil moisture stores will be part full and points will plot above the lines shown. Since initial losses are small on impervious surfaces, this will not change segments I and II greatly. However, segment III should be considered as a lower bound when the antecedent soil moisture of the pervious areas is low.

Plots of rainfall and runoff depths from storm events can therefore give information on the sizes of the various contributing surfaces and their initial loss values. The data can also give the relative frequency of runoff from pervious and impervious surfaces, and the magnitudes of these contributions.

In this study, storm rainfall and runoff data from 380 events on nine urban basins in Australia were analysed to provide this information. An additional 383 events from 17 urban basins in other countries were included for comparison.

DETAILS OF CATCHMENTS AND STORMS

Urban basins

Table 1 gives details of the 26 urban basins. Nine are located in Australia, the first four near to Sydney, the next four in Canberra and the last, Vine Street, in Melbourne. Details of the remaining basins were obtained from the Urban

Table 1 Details of urban drainage basins

Basin	Code	Country	Area	Impervious fraction	Directly connected impervious fraction	Urban percent	Land use %			Sewer type	Roof water connected
			ha			%	R	C/I	P		
Maroubra	MAR	Australia	57.3	0.52	0.16	100	75	17	8	S	No
Strathfield	STR	Australia	234	0.50	0.18	100	94	4	2	S	No
Jamison Park	JAM	Australia	22.1	0.36	0.33	100	83	0	17	S	Yes
Fishers Ghost	FGC	Australia	226	0.36	0.33	100	86	2	12	S	Yes
Giralang	GIR	Australia	94	0.25	0.25	85	85	0	15	S	Yes
Long Gully	LGC	Australia	490	0.05	0.05	16	16	0	84	S	Yes
Mawson	MAW	Australia	445	0.26	0.26	86	57	0	43	S	Yes
Curtin	CUR	Australia	2690	0.17	0.17	57	36	3	61	S	Yes
Vine Street	VIN	Australia	70	0.37	0.31	100	86	10	4	S	Yes
Pompano Beach	POM	USA	15.4	0.44	0.06	100	100	0	0	S	No
Sample Road	SAM	USA	23.5	0.36	0.18	100	0	100	0	S	-
Fort Lauderdale	FTL	USA	7.7	0.98	0.98	100	0	98	2	S	Yes
Kings Creek	KING	USA	5.26	0.71	0.44	100	100	0	0	S	No
Gray Haven	GRAY	USA	9.4	0.52	0.45	100	100	0	0	S	No
Malvern	MAL	Canada	23.3	0.34	0.34	100	100	0	0	S	Yes
East York	YORK	Canada	155	0.49	0.44	100	89	7	4	C	Yes
Clifton Grove	CLI	GB	10.6	0.40	0.40	100	100			S	Yes
St Marks Road	STMK	GB	10.3	0.56	0.56	100	100			S	Yes
Porsoberg	POR	Sweden	13	0.40	0.28	100	100			S	Yes
Munkerisparken	MUN	Denmark	6.44	0.46	0.31	100	100			C	Yes
Livry Gargan	LIV	France	235.5	0.33	0.33	78	78		22	C	-
Miskolc	MIS	Hungary	25.4	0.15	0.15	52	52		48	S	-
Luzzi	LUZ	Italy	1.73	0.85	0.85	100	100	0	0	S	Yes
Vika	VIK	Norway	10.1	0.97	0.97	100	0	100	0	S	Yes
Miljakovic	MIL	Yugoslavia	25.5	0.37	0.20	100	100			S	-
Kotta	KOT	Japan	1281	0.23	0.23	84	84	0	16	S	Yes

Drainage Basins UDC publication by Maksimovic & Radojkovic (1986a), except for the Kotta River basin in Japan, which came from Maksimovic & Radojkovic (1986b). Additional information on the impervious and impervious connected area was obtained, where possible, from the authority responsible for each of these basins.

Basin sizes ranged from 2 to 2690 ha and impervious fractions from 0.05 to 0.98. Nineteen of the basins are fully urbanized. For the other seven, urbanization ranged from 16 to 86%. At one extreme is Long Gully Creek which is only 16% urbanized, with an impervious fraction of 0.05. At the other extreme is Fort Lauderdale shopping mall which is almost entirely impervious. A distinction is made between the fraction urbanized and the fraction impervious. The presence of parks and gardens always reduces the impervious fraction below the urbanized fraction. All impervious fractions in Table 1 were reported to be measured from maps.

Land use is residential on 23 of the basins, mainly single family dwellings except on the King's Creek, Miljakovac and Kotta River basins which had low rise apartments. Of the remaining three basins, Sample Road is crossed by a six lane highway with commercial/industrial land use; Fort Lauderdale is a shopping mall with 98% impervious surfaces; and Vika is a city centre with 97% impervious surfaces.

Certain basins have specified areas of parkland. These include all nine Australian basins, Pompano, Sample Road, Fort Lauderdale, King's Creek, Gray Haven, Malvern, East York, Luzzi, Vika and Kotta (in some cases the parkland area is specified as zero). Other basins have some parkland, but the value is not specified. In these cases the parkland is incorporated into the predominant residential land use in Table 1. Three basins have large undeveloped areas (Livry Gargan, Miskolc and Kotta River). For these the undeveloped area is considered as parkland, and the developed as residential land.

The drainage systems are separate domestic and stormwater sewers in 23 basins, and combined sewers in three. Roof water is connected into the drainage system in almost all cases.

Most drainage systems are piped, except Pompano Beach where stormwater flows along grass ditches into a limited pipe system, and Luzzi where water flows along streets into a limited pipe system. King's Creek and Gray Haven have considerable flow lengths along grass ditches and gutters respectively before reaching the pipe system.

Storm events

Table 2 gives details of the 763 storm events. Rainfall depth is the total depth in the storm. Runoff depths were obtained by integrating under the recorded streamflow hydrograph then dividing by the total basin area, and are therefore an average depth of runoff for the total basin. St. Mark's Road basin had three streamflow recorders, one in the upper basin, one for runoff from the middle and upper basin, and a third for runoff from the total basin. Examination of the data showed that the sub-basin contributing to each recorder had the same land use and very similar impervious fractions, and also that the rainfall-runoff plots were very similar. Therefore all events for St. Mark's Road were considered together. Miljakovac basin also had two streamflow recorders, and produced similar results from the sub-basin and total basin, and so the rainfall-runoff events from the two were considered together.

Additional storm events were obtained for Pompano, Sample Road, Fort Lauderdale and King's Creek from Mustard *et al.* (1987), for Gray Haven from Wenzel & Voorbees (1980), and for Miscolc from Wisnovszky (personal communication).

Data from the Australian basins covered a very wide range of storm sizes, with average recurrence intervals generally in excess of 50 years for the larger storms. The USA, Canadian and Japanese basins had a similar wide range of storm sizes. Storm depths on the European basins tended to be smaller, with fewer events, particularly for Porsoberg and Munkerisparken.

Table 2 *Details of storm events*

Basin	Number of events	Number of impervious events	Range rainfall depths	Initial loss	Effective impervious fraction	Correlation coefficient
			mm	mm	F_i	
Maroubra	39	38	3.8-227	0	0.157	0.992
Strathfield	78	64	2.0-362	0	0.289	0.907
Jamison Park	85	48	0.6-111	0	0.207	0.961
Fishers Ghost	23	12	12.5-171	0	0.252	0.586
Giralang	35	29	2.2-36.7	3.26	0.349	0.954
Long Gully	35	22	5.3-69	0	0.059	0.803
Mawson	37	28	3.5-70	0	0.208	0.953
Curtin	37	21	1.9-42.0	0	0.174	0.875
Vine Street	11	4	14.2-124	0	0.306	0.670
Pompano Beach	32	30	2.0-33.3	1.24	0.069	0.844
Sample Road	42	41	1.3-64	0.19	0.268	0.950
Fort Lauderdale	31	31	4.6-55	1.33	0.957	0.978
Kings Creek	11	11	6.6-57	6.12	0.750	0.992
Gray Haven	21	18	5.6-59	3.72	0.483	0.990
Malvern	24	24	3.0-37.6	1.08	0.337	0.975
East York	13	13	1.5-24.3	1.31	0.478	0.967
Clifton Grove	25	25	0.5-6.7	0.51	0.239	0.980
St Marks Road	32	32	2.4-13.6	0.07	0.299	0.947
Porsoberg	7	7	1.4-11.1	0.57	0.208	0.996
Munkerisparken	8	8	2.6-14.5	0.43	0.351	0.995
Livry Gargan	38	38	1.5-28.9	0.56	0.174	0.968
Miskolc	17	14	0.4-44.7	0	0.133	0.979
Luzzi	30	28	1.0-21.2	0	0.580	0.976
Vika	14	14	0.8-14.2	0.23	0.652	0.992
Miljakovac	16	16	0.8-19.5	0.40	0.200	0.939
Kotta	22	9	14.5-263	1.17	0.316	0.939

RESULTS

Observations of rainfall and runoff depths

Plots of rainfall and runoff depths were constructed for all basins, and Fig. 2 shows typical results.

A difference between basins in Australia and other countries was immediately apparent. In the other countries the data tended to plot as a straight line having little scatter, with only a few isolated points lying above the line. This

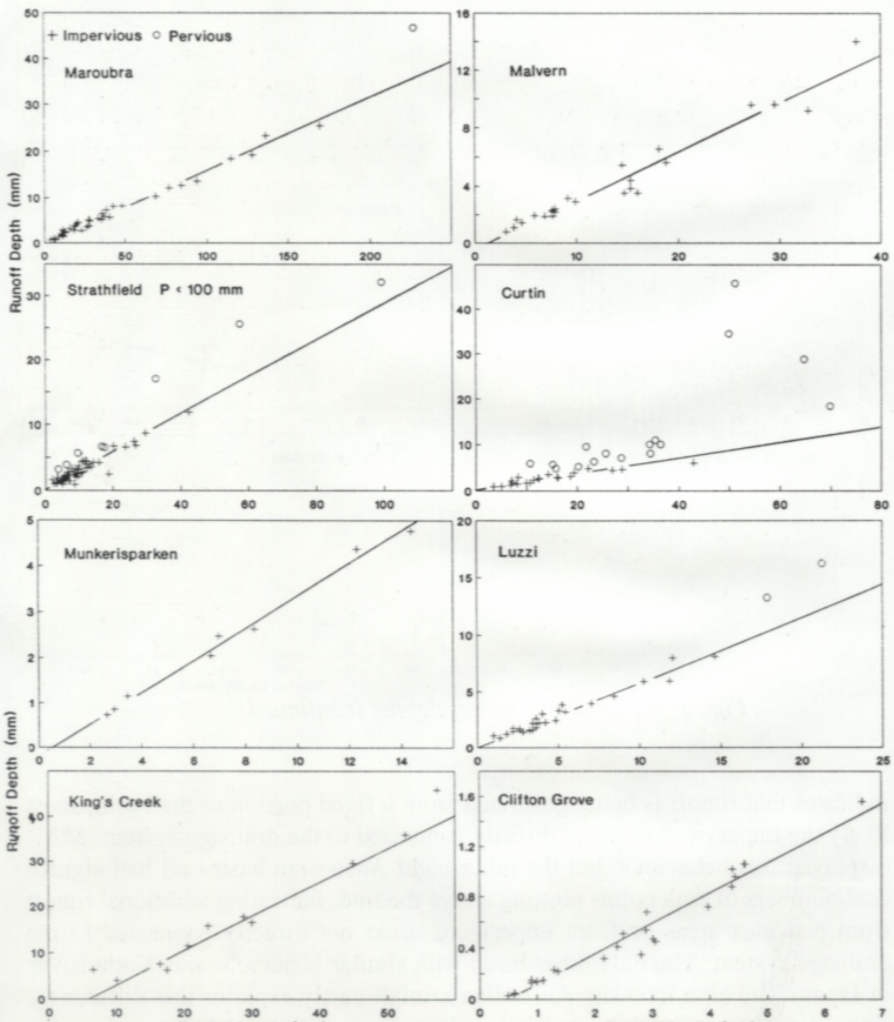

Fig. 2 Rainfall and runoff depths.

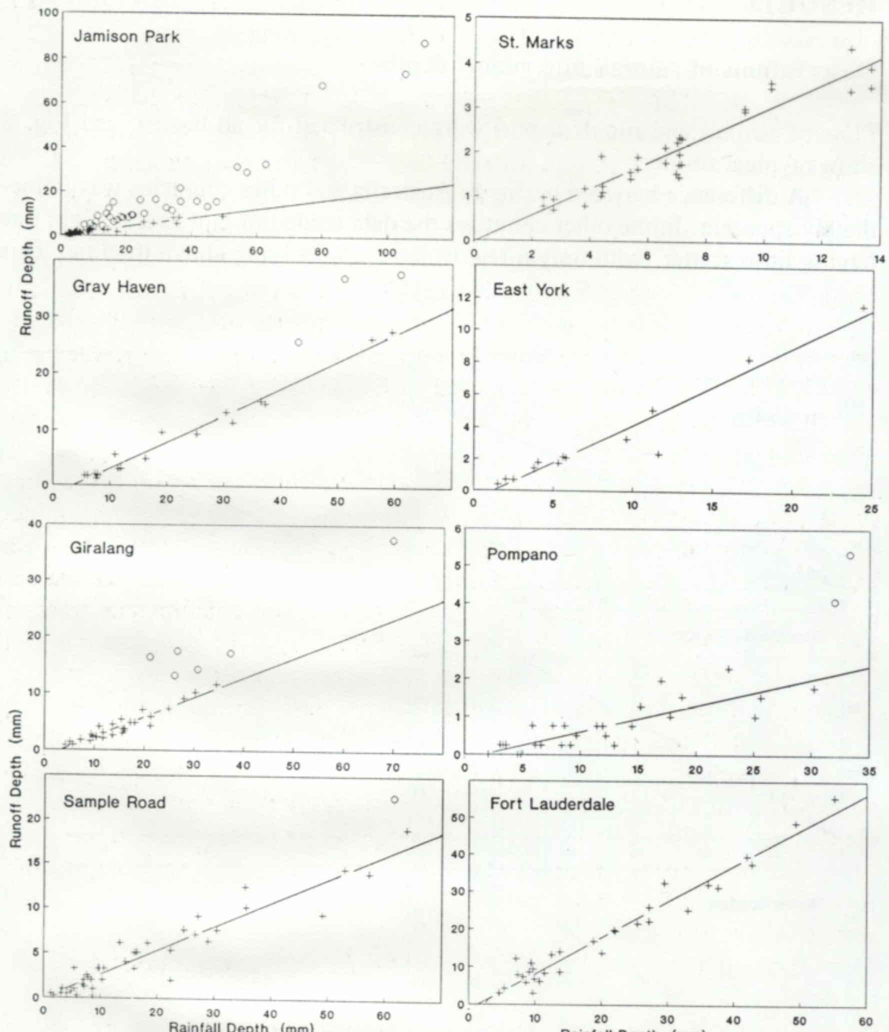

Fig. 2 Rainfall and runoff depths (continued).

indicates that runoff is being generated from a fixed portion of the basin, most likely the impervious surfaces directly connected to the drainage system. MAR displayed this behaviour, but the other eight Australian basins all had significant numbers of data points plotting above the line, indicating additional runoff from pervious areas or from impervious areas not directly connected to the drainage system. The only other basin with similar behaviour was Kotta River in Japan. The high intensity Australian rainfall partly explains this difference, since runoff from unconnected impervious areas will not reach the drainage system in small storms, but may flow across pervious surfaces to drains in large storms. However, the pervious surfaces themselves have also been observed to generate runoff in large storms in Australia.

Pervious area runoff was essentially absent for 17 of the 26 basins (MAR, POM, SAM, FTL, KING, GRAY, MAL, YORK, CLI, STMK, POR, MUN, LIV, MIS, LUZ, VIK, MIL). These basins showed very little scatter, with the data plotting close to a straight line, with an offset along the rainfall axis. The absence of pervious area runoff on these basins can be explained by the storm size, soil type and land use. MAR basin in Australia consists of sandy soil with very high infiltration rates. Only one storm, with 227 mm of rainfall, generated pervious area runoff. FTL, VIK and LUZ basins have very high impervious fractions, with little opportunity for pervious runoff to occur. Sample Road similarly has a major highway draining to the storm sewer, with sandy soil on the remainder of the basin. CLI, STMK, POR, KLO and MUN are all small basins, have small storms in the data and apparently do not generate pervious runoff.

Two basins gave unexpected results. POM, with sandy soil and a very limited drainage system (drainage to ditches with no kerbs and gutters), might not be expected to generate pervious runoff, but had quite a scatter in the data and at least two pervious runoff events. Note that the directly connected impervious fraction (0.06) is much smaller than the total impervious fraction (0.44). What appears to be happening is that runoff from the directly connected impervious surfaces always reaches the basin outlet (the effective impervious fraction determined from rainfall-runoff plots in the following section is close to 0.06). Additional runoff from the unconnected impervious surfaces flows across the pervious surfaces and a variable proportion of it reaches the basin outlet. The other basin, LIV, is relatively large with a significant area of parkland and might be expected to generate pervious runoff, but did not.

The nine basins which clearly showed pervious runoff were eight from Australia and KOT from Japan. All these basins are large and all had large storms in the data set.

From plots of rainfall and runoff depths, the following observations were made:

(a) the small basins, less than about 25 ha, which have an extensive storm sewer system tend to produce impervious runoff only. Larger basins tend to generate pervious as well as impervious runoff;

(b) the nine basins which showed clear evidence of pervious runoff had larger storms in the data set. However, pervious runoff also occurred for the smaller storms on these basins, whenever rainfall depths were greater than about 10 mm;

(c) basins with pervious runoff had greater scatter in the data than those with impervious runoff only, indicating that small amounts of pervious runoff occurred for most storms on these basins; and

(d) on all basins it was possible to identify events which were most probably impervious runoff alone, and so calculate the effective impervious area from the rainfall-runoff data. It was also possible to identify the offset on the rainfall axis and so calculate the impervious area initial loss.

From examination of the rainfall-runoff plots, it was decided to continue the investigation in stages, firstly, to study impervious events on all basins and secondly, to study pervious runoff on the nine basins where it occurred.

Analysis of impervious runoff events

The first analysis involved the 17 basins in which impervious runoff events could be clearly identified.

Some studies have found impervious rainfall-runoff data to plot as several straight line segments of increasing slope as in Fig. 1, indicating increasing size of contributing impervious area as the storm size increases (Miller, 1978; Jennings & Doyle, 1978, for SAM; Calomino & Veltri, 1984, for LUZ; Pratt *et al.*, 1984, for CLI). Variation from a single straight line, however, is not large in those studies. This is supported by the regressions of Driver & Troutman (1989) using the USA urban stormwater data base (142 basins) where the exponent, d, of the fitted power relation $Q = cP^d$ was on average 1.06 indicating the data plotting almost as one straight line. Analysis of the data in the present study did not show any clear evidence of more than one straight line. Therefore a least squares linear regression of the form $Q = a + bP = (P - IL_i)F_i$ was fitted to the data, where: Q = total depth of runoff for the storm; P = total depth of rainfall; IL_i = initial loss for the impervious surfaces; and F_i = effective impervious fraction, estimated from storm data.

Seven basins (MAR, POM, SAM, KING, GRAY, MIS, LUZ) had small numbers of apparently pervious runoff events in the data set and these events were omitted from the analysis. The criterion applied for omitting these events was that the runoff depth had to lie more than 1 mm above the regression line.

Results of the regressions are given in Table 2. Correlation coefficients were high for all 17 basins. Initial loss values in Table 2 range up to 6 mm (average 1.4 mm) and are quite consistent with values reported by other workers (Tholin & Keifer, 1960 (1.6 mm); Miller *et al.*, 1978 (4.0 mm); Melanen & Laukkanen, 1981 (0.4 to 1.0 mm); Ando *et al.*, 1986 (2.0 mm); and Hollis & Ovenden, 1988 (0.5 mm) for roof and road surfaces).

The effective impervious fractions (F_i) obtained from the regressions should be related to the impervious fraction measured from maps. Least squares regressions of F_i against map values of total impervious fraction A_i/A and directly connected impervious fraction A_{ic}/A gave (when forced through the origin):

$F_i = 0.74\ A_i/A \qquad r = 0.83 \qquad N = 17$ basins

$F_i = 0.85\ A_{ic}/A \qquad r = 0.82$

Except for MIL, values of A_{ic} in Table 1 were reported to be based on basin maps and photographs, and not on measurements of rainfall and runoff.

The analysis was next extended to the remaining nine basins which had pervious as well as impervious runoff events. This required that the pervious runoff events be identified and omitted from the analysis. A similar criterion (deviation exceeding at least 1 mm) was applied. In addition, the smaller events on each basin, where pervious runoff did not appear to be present, were analysed separately. Several regressions were made for each basin, omitting the various suspected pervious runoff events and examining the smaller events, and the most consistent result was selected. The results are shown in Table 2. Although the correlation was lower for these nine basins than the original 17, good results were obtained for all basins except FGC and VIN. In FGC the lower basin consists of parkland draining to a natural creek. VIN has expansive clays in which surface cracks close as the soil becomes wet. These factors may contribute to the slightly greater variability in the results for these basins. When effective impervious fraction (F_i) from the regressions was plotted against map impervious fraction, however, these two basins fitted very well with the other 24. Regression gave:

$F_i = 0.75\ A_i/A$ $\quad r = 0.83 \quad N = 26$ basins

$F_i = 0.86\ A_{ic}/A$ $\quad r = 0.83$

Results for the set of 26 basins therefore are very similar to the smaller set of 17 basins.

These relationships compare well with those of Melanen & Laukkanen (1981) for seven basins in Finland, and with Jensen (1990) for six basins in Denmark, where the coefficients were near to 0.75 and 0.90 respectively. Combining the basins of the present study with these additional basins (Fig. 3) gave:

$F_i = 0.75\ A_i/A$ $\quad r = 0.86 \quad N = 38$ basins

$F_i = 0.87\ A_{ic}/A$ $\quad r = 0.87$

In 21 basins the effective impervious fraction F_i was essentially less than or equal to the directly connected impervious fraction A_{ic}/A, in four basins F_i lay between the directly connected and total impervious fractions, while only one basin had F_i significantly larger than A_i/A. In most basins therefore, impervious runoff is generated on a portion of the directly connected impervious surfaces.

Pervious and impervious contributions to runoff

Separation of events into impervious and pervious area runoff allowed an assessment of the relative contributions of each type to stormwater runoff. Ten basins (FTL, MAL, YORK, CLI, STMK, POR, MUN, LIV, VIK and MIL) produced runoff from impervious surfaces only. As noted previously, these are small basins with well developed extensive drainage systems and relatively small storms. Seven basins (MAR, POM, SAM, KING, GRAY, MIS and LUZ) had a small number of outliers which could be interpreted as pervious runoff events. On average, these made up 6.6% of the total number of storms. Maroubra basin, with its highly permeable sandy soils, clearly generates only impervious runoff

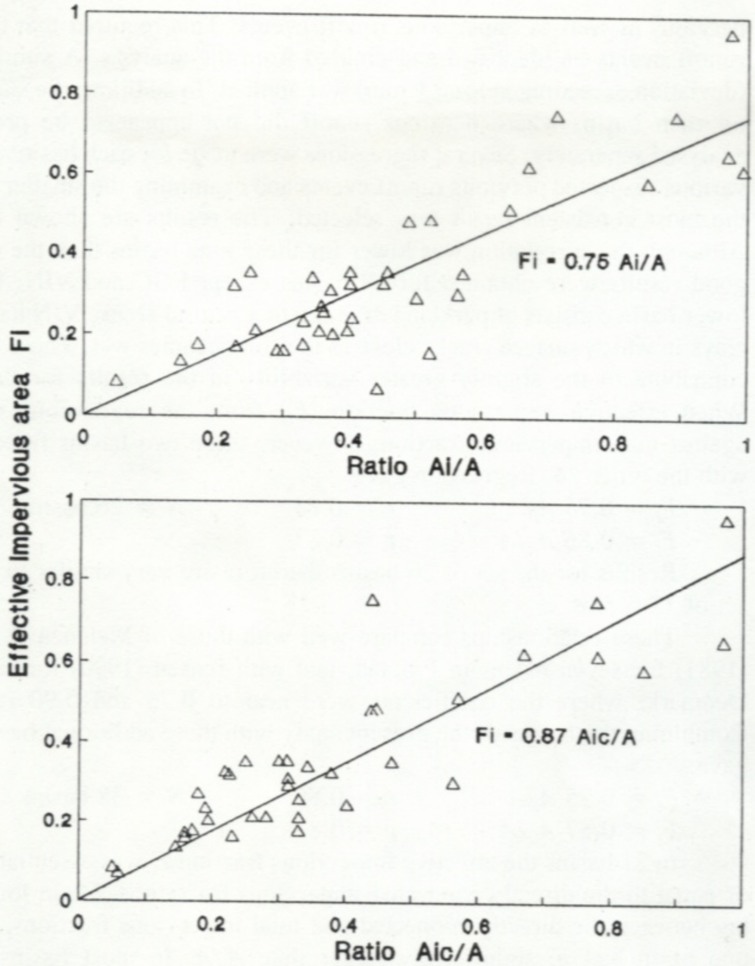

Fig. 3 Effective impervious fractions.

for 38 of the 39 events. The one event where pervious runoff does occur is noteworthy, because a very large storm (227 mm) produced 36 mm of impervious and 11 mm of pervious runoff. The Maroubra result shows the potential for pervious area runoff even on otherwise impervious area dominated basins if the storm is large enough.

The association of pervious runoff with the larger storms was also apparent in the remaining nine basins (STR, JAM, FGC, GIR, LGC, MAW, CUR, VIN and KOT) which showed clear evidence of pervious area runoff. These basins are all large and contain large storms in the data set. Details are given in Table 3. Significant pervious area contributions were present in 35% of the storms on average (range 17-64%), (column 1). For these, the proportion of total runoff volume contributed from impervious surfaces ranged from 15% (for an event on LGC) to 91% for an event on KOT (column 2). On average, impervious surfaces contributed 52% of the total runoff volume.

The dominant role of the impervious surfaces becomes more apparent when it is realized that the effective impervious surfaces occupy a much smaller fraction of the basin than do pervious surfaces, ranging from 0.06 to 0.35 for these nine basins (Table 2). Comparing the actual depth of runoff from impervious surfaces to depth of runoff from the pervious surfaces (column 3), runoff depths were up to 25 times greater, and 5.2 times greater on average.

Table 3 *Contributions of pervious and impervious surfaces to runoff*

Basin	Events with pervious runoff (1)	Ratio of impervious to total runoff volume* (2)		Ratio of impervious to pervious runoff depths (3)	
	%	Range %	Mean %	Range	Mean
Strathfield	17.9	35-89	58	1.32-20.0	4.76
Jamison Park	43.5	22-88	47	1.09-25.0	4.76
Fishers Ghost	47.8	38-78	55	1.82-10.0	4.17
Giralang	17.1	38-69	57	1.15-4.24	2.79
Long Gully	37.1	15-68	36	1.98-23.3	7.32
Mawson	24.3	18-74	57	0.58-7.60	4.53
Curtin	43.2	19-75	52	1.15-14.0	6.31
Vine Street	63.6	42-80	58	1.64-9.09	3.85
Kotta	59.1	40-91	65	1.43-20.0	6.25

*For those events with both pervious and impervious runoff.

Analysis of pervious runoff events

With the impervious contribution to runoff identified, the runoff from the remainder of the basin in combined pervious plus impervious events could be calculated by subtraction:

$$Q_p = Q - Q_i = Q - F_i(P - IL_i)$$

Figure 4 shows rainfall and runoff depths for STR basin (three small events are omitted for clarity). Some limiting conditions may be considered:

(a) if pervious runoff is zero (i.e. storm rainfall has not satisfied losses on the pervious areas) the points lie on line (1) and $Q = Q_i$;

(b) if the basin is fully wetted from prior storms, and 100% runoff occurs from both pervious and impervious surfaces, the points lie on the 45° line (2); and

(c) more generally, runoff will come from both impervious and pervious surfaces and data points will lie between lines (1) and (2). If the pervious area initial loss is independent of soil moisture condition and remains constant for all storms, then the points should lie on one line (say line (3), which is a least squares fit to the points). The fraction of the basin

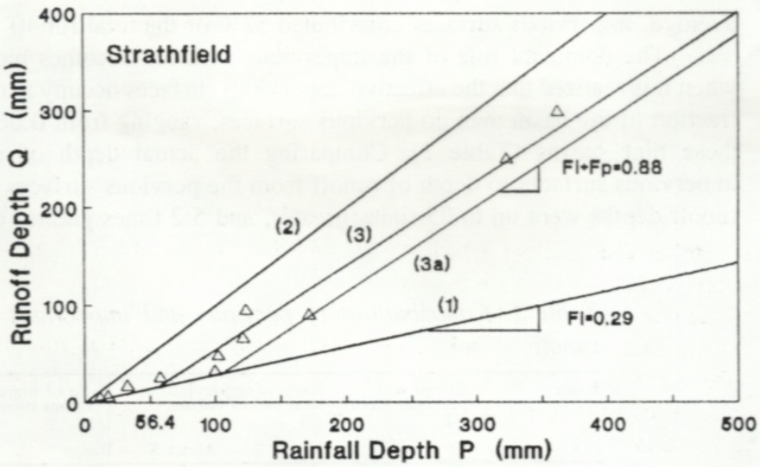

Fig. 4 Pervious runoff depths.

which contributes pervious runoff (F_p) is equal to the slope of line (3) minus the slope of line (1), i.e. $F_p = 0.59$. This is likely to include impervious surfaces which are not directly connected to the drainage system, plus a portion of the pervious surfaces. Note that Q_p is the pervious runoff depth averaged over the total basin. The actual runoff depth from the contributing "pervious" surfaces is Q_p/F_p. The initial loss IL_p on the pervious surfaces is given by the intersection of lines (3) and (1), i.e. $IL_p = 56.4$ mm.

Analysis of pervious runoff data may allow identification of the type of process occurring. If pervious runoff comes from a fixed source area and initial loss is independent of basin wetness, the points should lie on one straight line (3). If the source area is fixed but initial loss varies, the data should lie on parallel lines (3(a) etc.) depending on the value of the antecedent wetness. Alternatively, if the source area is not fixed but varies from storm to storm, then the data should lie on lines of varying slope, becoming steeper for the larger storms or for higher antecedent wetness.

Of the three Sydney basins, two (STR, JAM) showed a slight tendency to increasing source area for storms larger then 50 mm rainfall, while the third (FGC) did not. For all three basins the pervious runoff data plotted about a single line with little scatter, indicating that the storm rainfall depth was the major cause, with antecedent conditions having a minor effect. The behaviour of the four Canberra basins (GIR, LGC, MAW, CUR) were consistent with one another, with pervious runoff plotting about a single line for rainfalls less than 40 mm. For larger storms, considerable scatter in the pervious runoff indicated that factors other than storm rainfall were acting. Examination of the average rainfall intensity in the storm and measures of antecedent wetness (1-day and 5-day prior rainfalls, 5 day API, number of preceding dry days) for these pervious runoff events showed a definite trend for pervious runoff to increase with higher rainfall intensities and wetter antecedent conditions, pointing to the possibility of using these variables to predict pervious runoff.

CONCLUSIONS

Storm rainfall and runoff depths from 380 events on nine Australian basins plus a further 383 events on 17 basins from other countries have been investigated. Impervious surfaces are the major contributor to runoff on 17 of the 26 basins. These basins are mostly less than 25 ha and have small to medium size storms in the data sets. They include all overseas basins (except Kotta in Japan), plus one Australian basin (Maroubra). Of the nine basins which had significant quantities of runoff from pervious as well as impervious surfaces, eight were located in Australia and one (Kotta) in Japan. These were all larger basins and had larger storms.

From plots of rainfall and runoff depth, the effective impervious area was determined for all 26 basins. This was found to be related to the sizes of the impervious and impervious connected areas estimated from basin maps. The data indicate a fixed area of effective impervious surfaces for both small and large storms. Division of the total impervious area into impervious connected plus additional impervious surfaces which are sometimes active does not appear to be warranted.

For the nine basins with significant amounts of pervious runoff, the largest quantities of pervious runoff occurred in the larger storms. For storms less than 40 or 50 mm rainfall depth, pervious runoff depended mainly on the depth of rain in the storm, while for larger storms rainfall intensity and antecedent wetness also had an effect.

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