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MODELLING RUNOFF FROM PERVIOUS AND IMPERVIOUS SURFACES IN URBAN CATCHMENTS

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INTRODUCTION

In urban catchments stormwater runoff comes partly from impervious and partly from pervious surfaces. The impervious surfaces can be directly connected to the drainage system, in which case rainfall losses are very small, travel times are short, and the impervious surfaces respond very rapidly to rainfall. Pervious surfaces have larger rainfall losses, lower flow velocities and consequently slower response to rainfall.

This study examines runoff depths and lag times for directly connected impervious surfaces and pervious surfaces, using recorded rainfall and flood hydrograph data for 9 urban catchments in Australia.

STUDY CATCHMENTS

Table 1 gives details of the catchments and storm events. Land use in all cases is mainly separate residences, with some commercial areas. The urban fraction is the proportion of the catchment which has been developed for urban use. The impervious fraction is the total amount of impervious surfaces, made up of roofs, roads, and other paved surfaces. Both of these fractions were measured from maps.

RAINFALL AND RUNOFF DEPTHS

Plots of rainfall and runoff depths can be used to determine the directly connected impervious fraction in urban catchments (Miller et al, 1978). Figure 1 shows results for Giralang catchment. The slope of the fitted line gives the directly connected impervious fraction, and the intercept on the rainfall axis gives the impervious surface initial loss. Most points, particularly for small events, plot about the directly connected fraction line. A few points, for larger events or for medium size events with high antecedent wetness, plot above the straight line.

Directly connected impervious fractions calculated from these plots are given in the last column of table 1. Boyd et al(1993) examined data for 26 urban catchments in Australia and other countries. The total impervious fraction measured from maps ranged from 29% to 98% of the urban fraction, the smaller value applying to typical separate residential developments, and the larger value applying to city centres and shopping malls. The directly connected impervious fraction determined from rainfall and runoff plots averaged 75% of the total impervious fraction measured from maps.

The runoff volumes V from impervious and pervious surfaces can be determined from :

$$Vtotal = Vimp + Vper = A.IMP.(P-ILimp) + Vper \qquad (1)$$

where A is the total catchment area, IMP is the directly connected impervious fraction, P is the total rain depth in the storm, and ILimp is the initial loss on the impervious surfaces. For each storm Vtotal is known from the runoff hydrograph, P is known from the recorded rainfall, and IMP and ILimp are known from the plot of rainfall and runoff depths. Therefore the total runoff can be split into contributions from the impervious and pervious surfaces. Runoff hydrographs from each surface type can then be calculated.

RUNOFF HYDROGRAPHS FROM PERVIOUS AND IMPERVIOUS SURFACES

Runoff hydrographs can be calculated using runoff routing techniques:

$$\text{Conservation of mass} \quad R(t) - Q(t) = dS/dt \qquad (2)$$

$$\text{Storage -discharge} \quad S = K.\,Q \qquad (3)$$

where R is the inflow to the catchment from rainfall (m^3/s), Q is the runoff from the catchment (m^3/s), S is the volume of water in temporary storage on the catchment surface, and K is the lag time. If the response is linear, K is constant. Alternatively, if the response is nonlinear the lag time varies as the discharge Q changes.

Equations (2) and (3) can be solved numerically:

$$Q_2 = (Q_1(K_1\text{-}0.5\Delta t) + (R_1 + R_2)0.5\ \Delta t)\ /\ (K_2 + 0.5\Delta t) \qquad (4)$$

where subscripts 1 and 2 indicate values at the start and end of the time step, and Δt is the time step. To calculate runoff hydrographs, values of the lag time K are needed for pervious and impervious surfaces.

LAG TIMES FOR NATURAL AND URBAN CATCHMENTS

Lag times for urban catchments will be significantly lower than for natural catchments as a result of higher flow velocities for overland flow, as well as for the more hydraulically efficient gutters, pipes and channels.

Considering the total catchment, Carter(1961) used 24 natural, partly urban, and fully urban catchments and determined that lag times for fully urbanised catchments were 0.17 those of natural catchments. Table 2 summarises lag relations determined by a number of workers. Some used the urban fraction U while others used the impervious fraction I.

The relations using 1 + U predict the lag time for a fully urbanised catchment to be between 0.15 to 0.25 of the natural catchment value. The relations using 1 + I predict the lag time for a fully impervious catchment to be between 0.27 to 0.32 of the natural catchment value. It is not clear from the paper of Rao et al(1972) whether 1 + I or 1 + U was used in the regressions. The paper refers to both impervious areas and built up areas. If the regressions actually used U then these results would agree quite well with those of Aitken(1975) and NERC(1975). The same applies to the results of Desbordes (1978) which include data from Rao et al(1972).

Espey et al(1977) and Schaake et al(1967) used I rather than 1+I. To calculate the ratio of urban to natural catchment lag time, a nominal value of I = 0.05 (i.e.5%) was used for the natural catchments. This ratio of fully impervious to natural catchment lag time, 0.46 to 0.58, was higher than all of the other studies. The catchments used by Schaake et al(1967) were all small, in most cases fully paved parking lots, and therefore these results apply more to overland flow rather than total cachment flows. It may be that urban lag ratios for total catchments, including gutter, pipe and channel flow are less than those for overland flow runoff from impervious surfaces. This would support the observation of Carter(1961) and Sauer et al(1983) that changes to the drainage system in urban catchments are more effective in reducing lag times in urban catchments than changes to the amount of impervious surfaces.

From Table 2 it can be expected that the lag time for a fully urban catchment will be approximately 0.2 that of an equivalent natural catchment, and the lag time for a fully impervious surface from 0.3 to 0.6 that of a grassed surface, however it must be noted that there is considerable variation in these results.

MODELLING RESULTS

From figure 1 it is apparent that in some storms runoff comes entirely from the impervious surfaces, while in others it comes from both pervious and impervious surfaces. This suggests that the urban catchment should be modelled with two parallel runoff routing elements, with higher rainfall losses and lag parameter for the pervious surfaces, and very small rainfall losses and lag parameter for the impervious surfaces. This model model can be applied to natural catchments by setting the impervious part to zero. As the catchment becomes urbanised, part of the pervious surfaces can be replaced by impervious with smaller rainfall losses and lag times.

For the natural part of the catchment, the lag relation of Askew(1970) was adopted :

$$Kper = c\ A^{0.57}\ Q^{-0.23} \qquad (5)$$

where K is the lag time (hours), A is the catchment area (km^2), and Q is the discharge from the catchment at time t (m^3/s). The scaling parameter c controls the magnitude of the lag time. The optimised value, by fitting calculated and recorded hydrographs, was found to be c = 1.7.

Runoff from impervious surfaces was assumed to have a small initial loss, usually between 0 and 2 mm, and zero continuing losses. Opinions vary as to whether runoff from impervious surfaces is linear or nonlinear, and in the abscence of strong evidence, the simpler linear response was adopted. This means that the lag time will depend only on catchment characteristics and not on the discharge. A relation between K and A was adopted, and values of the coefficient and power of the relation were determined by optimisation to fit calculated and recorded hydrographs using the 144 recorded floods on the 9 urban catchments of table 1. The resulting lag relation was :

$$Kimp = 0.1\ c\ A^{0.25} \qquad (6)$$

where c = 1.7 as in equation (5) and the lag reduction factor for impervious surfaces is 0.1.

The resulting model has been applied both to natural catchments and to the 9 urban catchments of table 1. Figure 2 shows optimised values of parameter c for these catchments. Note that the same value of c applies across a range of catchment sizes, indicating that the powers of A in equations (5) and (6) are correct. The model has also been found to apply across a range of flood sizes, indicating that the adopted linearity and nonlinearity for impervious and pervious surfaces is satisfactory.

CONCLUSIONS

Plots of rainfall and runoff depths for storms on urban catchments indicate that runoff is generated on both impervious and pervious surfaces, and the proportion generated on each surface varies from storm to storm. A general catchment model therefore can consist of these two surface types in parallel. For natural catchments, the impervious surfaces are set to zero and all runoff comes from the pervious surfaces. These have higher rainfall losses and larger lag times. For urban catchments, a portion of the pervious surfaces is converted to impervious, with very small rainfall losses and lag times. These impervious surfaces are directly connected into the stormwater drainage system and make up, on average, 75% of the total impervious surfaces measured from maps.

Application of the resulting model to 10 natural and 9 urban catchments has confirmed that it applies over a wide range of catchment sizes and impervious fractions, and over a range of flood events from quite small to very large.

For the catchments used in this study, the best value of the scaling parameter for the lag equations (5) and (6) was found to be $c = 1.7$ for both natural and urban catchments. The reduction factor for impervious surface lag time compared to natural catchment lag time was found to be 0.1. For catchments in other regions, these values can be optimised to fit calculated and recorded hydrographs if necessary.

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Table 1. Details of Urban Catchments and Storms

Catchment	National Station Number	Area km^2	Urban Fraction	Imperv-ious Fraction	Directly Connected Impervious Fraction	Number of Events	Rainfall Range mm
Curtin	410745	27.0	0.57	0.17	0.17	14	13-79
Mawson	410753	4.45	0.78	0.26	0.21	11	26-80
Long Gully Ck.	410746	4.94	0.16	0.05	0.05	14	26-65
Giralang	410763	0.94	0.70	0.25	0.22	14	5-79
Maroubra	213300	0.57	1.00	0.52	0.16	20	4-102
Strathfield	213304	2.31	1.00	0.50	0.29	20	2.5-139
Fisher's Ghost Ck.	213006	2.35	0.96	0.36	0.25	20	8-86
Jamison Park	-	0.21	1.00	0.36	0.21	20	1.0-54
Vine St.	230109	0.64	1.00	0.37	0.31	11	14-108

Table 2. Lag Relations for Catchments

Study	Number of Catchments	Catchment Size Range (ha)	URB Range	IMP Range	Relation
Aitken (1975)	6	80-5600	0.25-1.0		$A^{0.52}\ S^{-0.50}\ (1+U)^{-1.97}\ Q^{-0.28}$
Aitken (1975)	11	40-900	0.0-1.0		$A^{0.44}\ S^{-0.31}\ (1+U)^{-2.74}\ Q^{-0.28}$
Rao (1972)	13	12-5000		0.0-0.38	$A^{0.46}\ (1+I)^{-1.66}\ P^{-0.27}\ D^{0.37}$
Desbordes (1978)	21	0.4-5000		0.15-1.0	$A^{0.18}\ L^{0.15}\ S^{-0.36}\ (1+I)^{-1.9}\ P^{-0.07}\ D^{0.21}$
NERC (1975)	138	4-61700	0.0-0.84		$L^{0.14}\ S^{-0.38}\ (1+U)^{-1.99}\ RSMD^{-0.40}$.
Espey (1977)	41	0.04-39		0.02-1.0	$L^{0.23}\ S^{-0.25}\ I^{-0.18}\ \phi^{1.57}$
Schaake (1967)	19	0.09-62		0.09-1.0	$L^{0.24}\ S^{-0.16}\ I^{-0.26}$

P = total rain depth in storm   D = storm duration
RSMD = residual soil moisture deficit ϕ = channel improvement factor

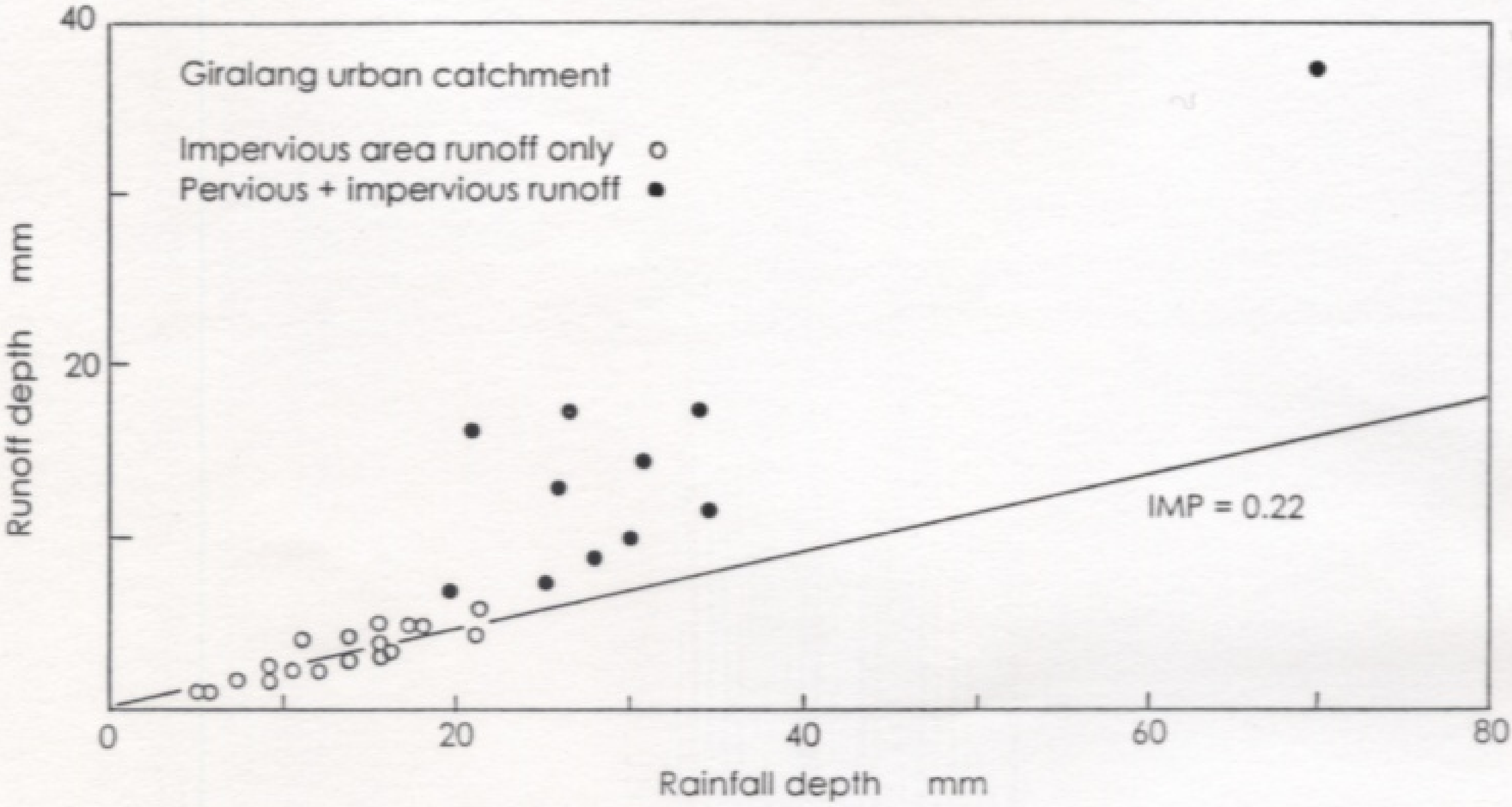

Figure 1. Rainfall and Runoff Depths

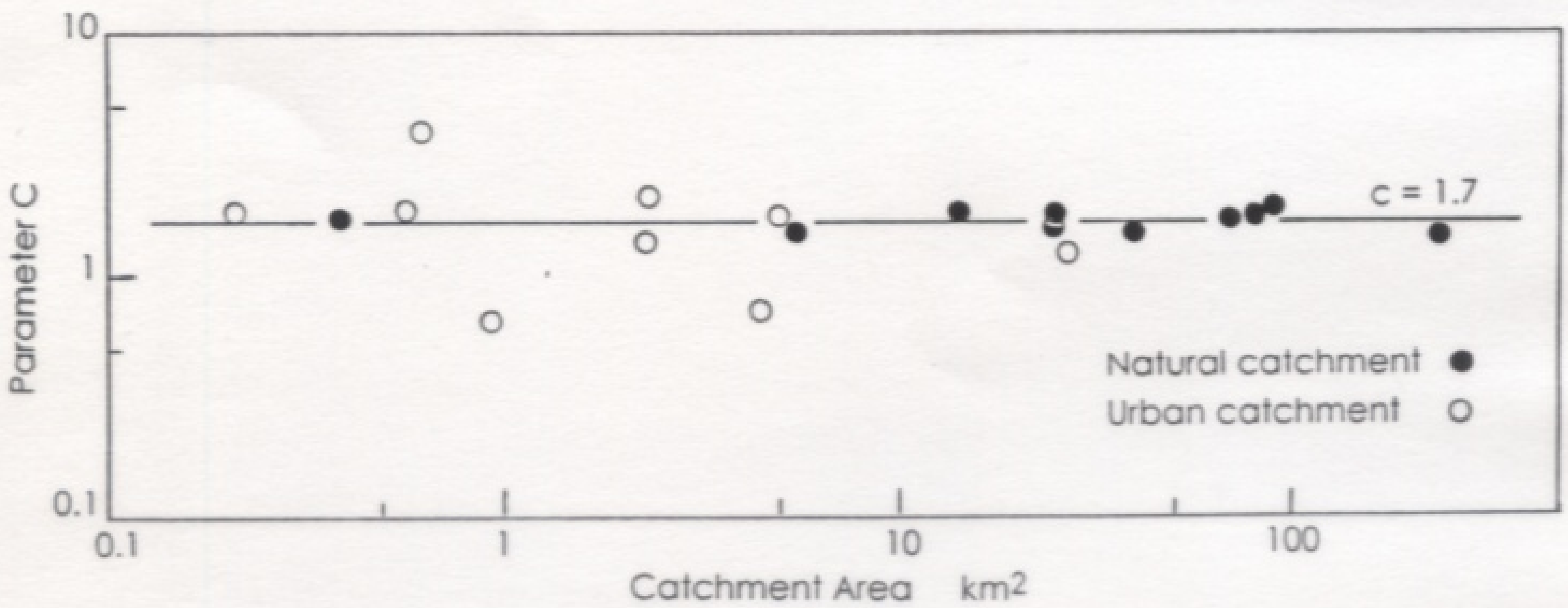

Figure 2. Lag Parameter c versus Catchment Size