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WBNM runoff routing parameters for south and eastern Australia

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SUMMARY: *The lag parameter C in the runoff routing model WBNM has been derived from recorded storms on 54 catchments in Queensland, NSW, Victoria and South Australia. Parameter C was found to be independent of flood size, catchment area, stream slope, and various storm and catchment characteristics. A review of studies on velocity variations within catchments, and lag time variations between catchments supports these results. The area-standardised lag parameters of several widely used runoff routing models are shown to be related to one another. From the study, a value of C = 1.6 is recommended for use on ungauged catchments.*

1 WBNM RUNOFF ROUTING MODEL

The WBNM runoff routing model was originally developed by Boyd, Pilgrim and Cordery, and is described by Boyd [1975] and Boyd et al. [1979]. Recent development has been by Boyd, Rigby and VanDrie [Boyd et al. 1999; 2002]. WBNM divides the catchment into subcatchments, based on the stream network and the surface contours defining each subcatchment. Two types of subcatchments are identified:

O*rdered basins* are at the uppermost end of each stream branch and therefore do not receive runoff from upstream subcatchments. They convert excess rainfall into a runoff hydrograph at the subcatchment outlet.

Interbasin areas are located lower on the stream branch and receive runoff from upstream subcatchments. Interbasin areas have a stream segment carrying this runoff from upstream areas. As well as transforming excess rainfall into runoff as for ordered basins, the interbasin areas also route the upstream runoff through the stream segment. As the storage characteristics and lag times of the two types of runoff are different, different storage or lag properties are allocated to them.

Each subcatchment routes runoff (from either excess rainfall or upstream runoff) through a nonlinear storage. Allocation of lag times to these two processes uses the following equations:

Routing of excess rainfall to runoff

$$K_i = C\, A_i^{0.57}\, Q^{-0.23} \qquad (1)$$

Routing upstream runoff hydrograph through the stream channel of an interbasin

$$K_i = 0.6\, F_i\, C\, A_i^{0.57}\, Q^{-0.23} \qquad (2)$$

where

K_i = *lag time of subcatchment i (hours) for use in runoff routing equations*

A_i = *subcatchment area (km^2)*

Q = *discharge at downstream end of the subcatchment (m^3/s)*

C = *a lag parameter for the entire catchment*

F_i is a factor depending on the type of stream reach. For natural streams, $F_i = 1.0$. For modified channels, F_i represents the ratio of travel times between the modified and natural channel, and is inversely proportional to the ratio of flood wave celerities or flow velocities.

Equations (1) and (2) indicate that travel times in major streams are 0.6 times those for overland flow and minor streams. The ratio 0.6 was derived empirically by analysis of observed hydrograph lag data [Boyd et al., 1979] and is supported by the tracing studies of Pilgrim [1976, 1977, 1982], where flow velocities in the main stream channels were found to be on average twice those than in smaller drainage lines.

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Equations (1) and (2) are based on the study of catchment lag time by Askew [1968, 1970]. The power –0.23 corresponds to a nonlinearity parameter value of m = 0.77 in other models such as RORB, RAFTS and URBS. The power of 0.57 for area indicates that lag or travel times are closely proportional to travel distances, since these are also related to catchment area raised to a power near to 0.57.

Equations (1) and (2) allocate a lag time to each subcatchment based on its size, and allows it to vary nonlinearly with flood discharge. WBNM requires the evaluation of only one parameter, the lag parameter C, to model a catchment. If equations (1) and (2) are valid, the same value of parameter C should apply to a wide range of catchments and a wide range of flood magnitudes. The objectives of the present study therefore are to test whether parameter C is independent of catchment physical properties, and of storm and flood characteristics, and also to determine values of parameter C which can be applied to ungauged catchments.

2 PREVIOUS STUDIES OF PARAMETER *C*

Parameter values have been previously derived for WBNM by Boyd et al. [1979], Sobinoff et al. [1983], and Boyd et al. [2002]. Plots of parameter C against catchment area A have shown no trend for C to vary with catchment size, indicating that the power of area A in equations (1) and (2) is satisfactory. Additionally, plots of C against the peak discharge of the recorded flood have shown no trend for C to vary with flood size, indicating that the nonlinearity parameter m = 0.77 is satisfactory.

For 10 catchments in the coastal region of NSW (0.4 to 250 km^2), Boyd et al. [1979] obtained a mean lag parameter C value of 1.68. For 17 catchments (0.1 to 800 km^2) in the Newcastle- Sydney-Wollongong region Sobinoff et al. [1983] obtained a mean C of 1.16. The difference in these two values may be attributed in part to different methods of analysis, including baseflow separation and different rainfall loss assumptions, as well as different calibration criteria.

Derived parameter values from different storms can also be expected to contain some scatter, partly due to errors in rainfall and streamflow data, including insufficient spatial raingauge coverage, but also due to limitations in the models themselves. Loy and Pilgrim [1989] quote typical errors of 10-20% for rainfall and 25% for streamflow data, with larger errors being quite possible.

The present study extends these results to 584 storms on 54 catchments in Queensland, NSW, Victoria and South Australia.

3 CATCHMENTS AND STORM DATA

Table 1 gives details of the 54 catchments. Catchment sizes ranged from 0.1 to 7300 km^2 and stream slopes from 0.9 to 152 m/km. Equal-area stream slope was used, defined as the slope of a straight line drawn through the elevation of the catchment outlet such that the area under the line is equal to the area under the plotted stream profile. Catchments were divided into between 1 and 140 subcatchments for modelling. The peak discharge of the largest flood in the data set for each catchment is given as an indication of the size of events modelled.

Queensland catchments were all located in the coastal drainage division 1 of the Australian Drainage Divisions, and NSW catchments almost all in coastal drainage division 2. Six of the Victorian catchments were located in drainage division 2 and 4 in drainage division 4. The South Australian catchments were from the Onkaparinga and Torrens basins in the Adelaide hills, drainage division 5. All catchments are predominantly in rural condition.

Rainfall and streamflow data was analysed by subtracting an initial loss based on the time when hydrograph rise commenced, and a continuing loss rate was then calculated to match excess rainfall depths with the recorded surface runoff depth. The end of surface runoff was identified from semi-logarithmic plots of hydrograph recessions, and surface runoff was separated from baseflow by joining the start and end points by a straight line. A comparison of the straight line method with curvilinear baseflow separation procedures such as those of Nathan and McMahon [1990] and Boughton [1995] found that differences in calculated surface runoff depth and peak discharge were only minor, due to the fact that baseflow was relatively small for most flood events analysed.

The lag parameter C was derived for each event by matching calculated and recorded surface runoff peak discharges, with a visual check that the hydrograph shape was reproduced adequately. Plots of parameter C against flood peak discharge were examined to confirm that there were no trends for C to vary with event size, and an average parameter C was then calculated for each catchment. These catchment average values are given in table 1.

4 RESULTS OF CALIBRATION

4.1 Variation of parameter *C* with flood magnitude

Possible variation of parameter C with flood size was examined by plotting C versus the peak flood discharge for all events on each catchment. For each state, catchments with reasonable numbers of flood events were selected for examination. From table 1 these were 112004, 112101, 112905, 212320, 212340, 214330, 214334, 214340, Stony Creek, 229136, 405261, 415224, 503502, 504512 and 504523. Visual examination of the plots for these 15 catchments indicated a slight increase in *C* as flood magnitude increased for 3 catchments, a slight decrease for 4 catchments, and no trend for the remaining 8 catchments. Significance tests were applied to the 7 catchments showing some trends, to determine if the slope of the trend line was significantly different from zero at the 5% level. On only 2 catchments was the slope significantly different from zero (Eastern Creek and Scotts Creek displayed a slight trend for *C* to increase for larger floods), the remainder showing no trend. The Eastern Creek result is affected by 2 of the 17 parameter *C* values, and Scotts Creek by 3 of 9 values being larger for larger floods. Overall, there is no strong trend for parameter *C* to vary, either increasing or decreasing with flood magnitude.

This result indicates that the power m = 0.77 in equations (1) and (2) satisfactorily models nonlinearity over these ranges of flood magnitudes. It is worth noting that this is very close to the value of 0.8 adopted in many applications of the RORB model. Figures 1 and 2 show plots of parameter *C* versus flood peak discharge for Cawleys Creek (214334) which did not show a trend, and Eastern Creek (212340) which did show a trend for *C* to increase. The majority of catchments showed no clear trends for *C* to vary with flood size.

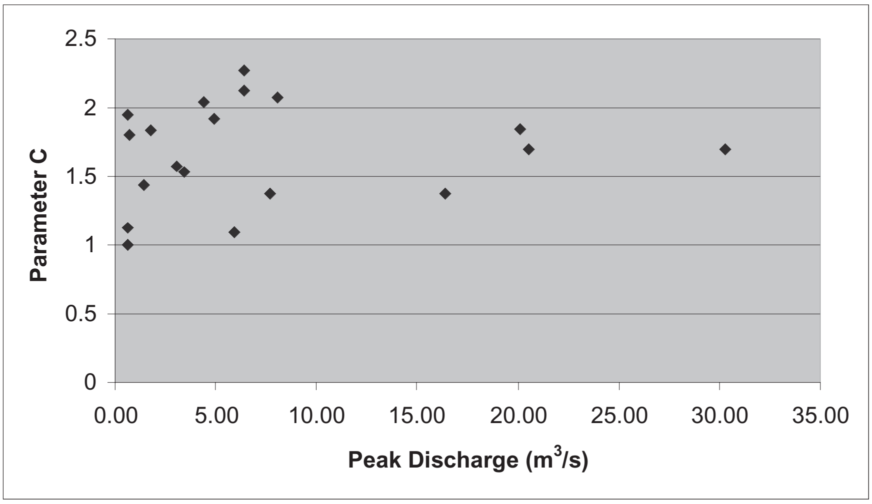

Figure 1: Parameter C versus flood discharge – Cawleys Creek (214334).

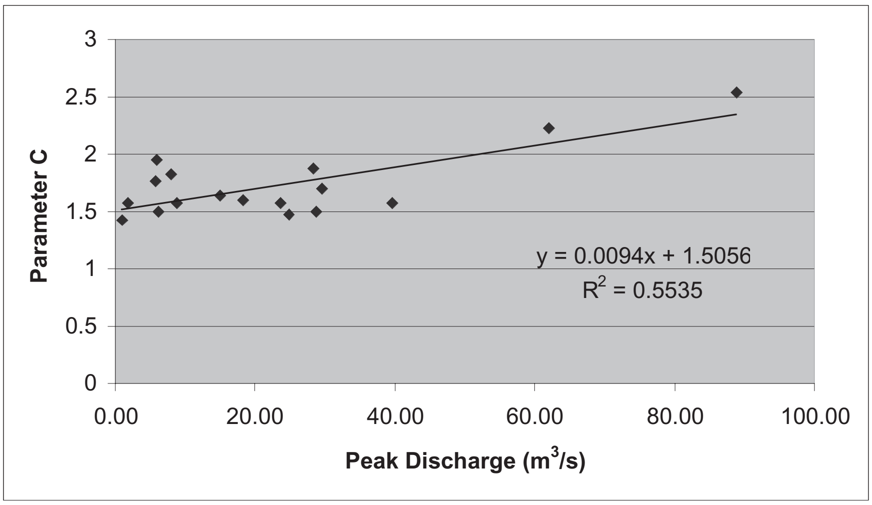

Figure 2: Parameter C versus flood discharge – Eastern Creek (212340).

4.2 Variation of parameter *C* with catchment area

Since the lag parameter *C* is independent of flood magnitude, a mean value was calculated for each catchment. Plots of catchment mean *C* values against catchment area were then made. For all four states, there was no trend for *C* to vary with catchment area. The average values of *C* were 1.47, 1.74, 1.74 and 1.64 for Queensland, NSW, Victoria and South Australia respectively. Since the value for Queensland is furthest from the overall mean, a 1 tailed significance test was carried out to determine if that mean was different from the mean of the remaining 37 catchments. The Queensland mean was found to be not significantly different from the remainder of the data at the 5% level.

The overall mean for all 54 catchments was 1.64. The overall mean, when weighted by the number of events on each catchment was 1.59.

Figure 3 shows catchment mean *C* values plotted against catchment area for all 54 catchments, clearly revealing no trend for parameter *C* to vary with catchment size. This result indicates that the power 0.57 in equations (1) and (2) satisfactorily describes the relation between lag time and catchment size.

4.3 Variation of parameter *C* with stream slope

Figures 4 to 8 show catchment mean parameter *C* plotted against equal area stream slope. The trend for the Queensland data is significant at the 5% level, but no trends are apparent for the remaining states, or for the combined data for all 54 catchments. The Queensland result is affected by high *C* values for 2 of the 17 catchments. Since there is no significant difference between mean *C* values for the 4 states, it is valid to combine results for all 54 catchments, and it is apparent that there is then no trend for *C* to vary with catchment slope, over a wide range from 0.9 to 150 m/km (figure 8).

4.4 Relation between parameter *C* and storm and catchment characteristics

Bodhinayake [2004] investigated possible trends in parameter *C* against a range of storm and catchment characteristics. Storm variables considered were the total hydrograph peak discharge, surface runoff peak discharge, total rainfall depth, excess rain depth, average rainfall intensity, peak rainfall intensity, location of peak burst within storm, ratio of peak to average rainfall intensity, ratio of excess rain depth to total rain depth, and spatial distribution of rainfall. Catchment variables were the area *A*, stream slope *S*, stream length *L*, length to centroid L_c, spatial distribution of area L_c / L, catchment shape A / L^2, catchment elevation, number of rain days, 2 year 72 hour design rainfall intensity, and mean annual rainfall. The study used 254 storms on 17 catchments in eastern Queensland.

While slight trends were apparent in some cases and for some subsets of catchments, there were no strong trends for *C* to vary with any of these variables. The independence of parameter *C* from these storm and catchment characteristics indicates that one value applies generally over a wide range of regions. A similar result has been obtained for the area-standardised lag parameter in RORB by Yu [1990] and Pearse et al. [2002].

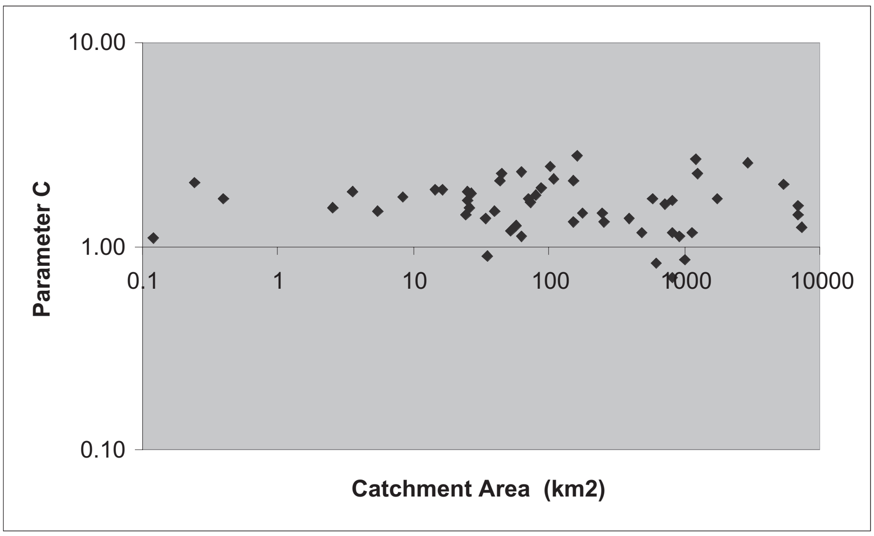

Figure 3: Parameter C versus catchment area – all 54 catchments.

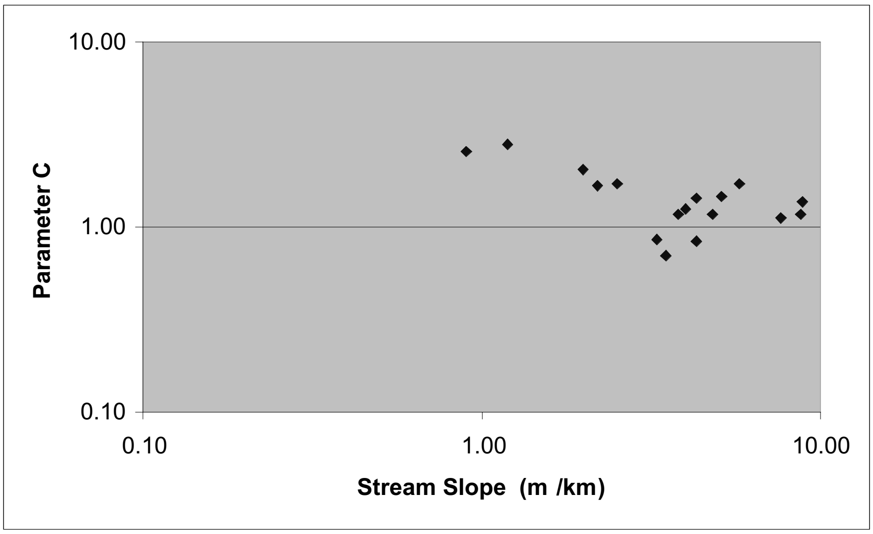

Figure 4: Parameter C versus equal area stream slope – Queensland.

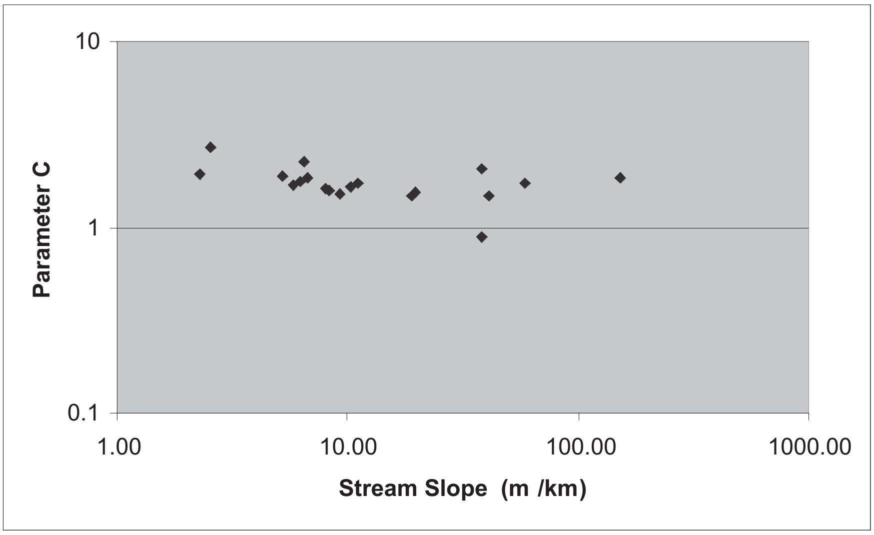

Figure 5: Parameter C versus equal area stream slope – NSW.

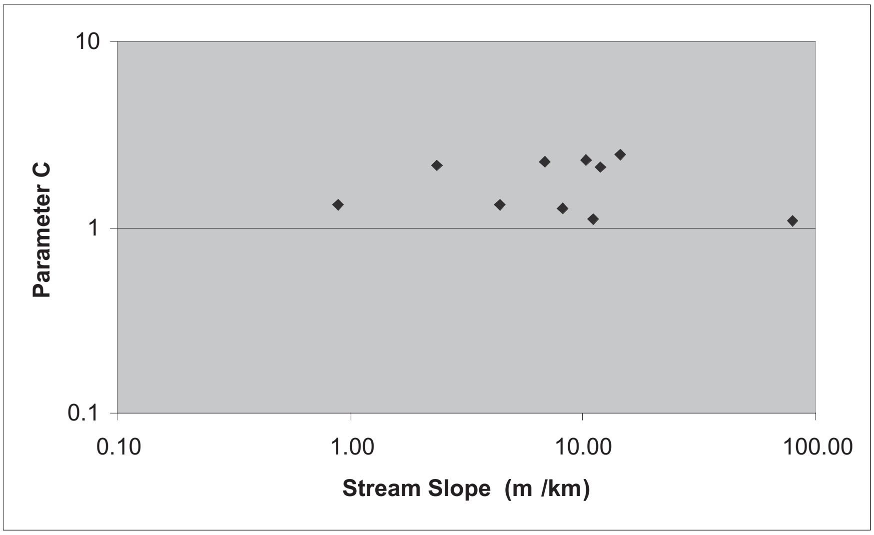

Figure 6: Parameter C versus equal area stream slope – Victoria.

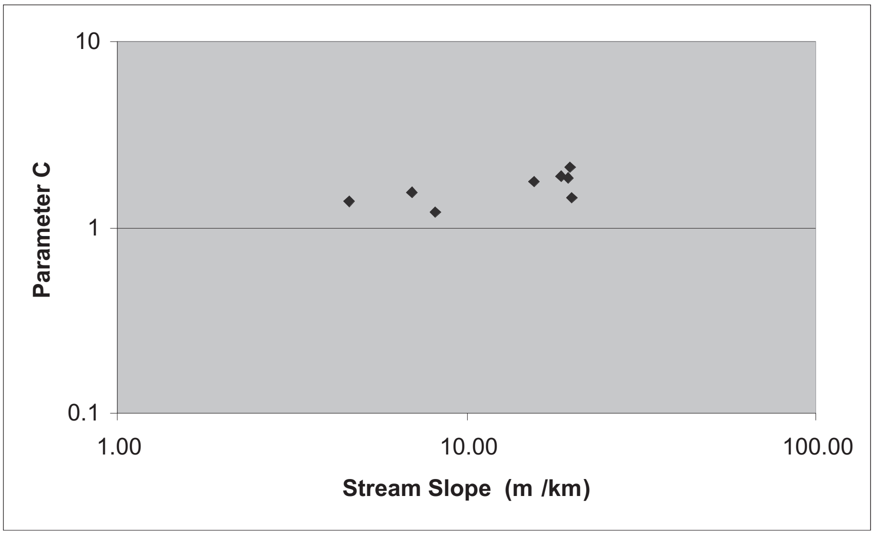

Figure 7: Parameter C versus equal area stream slope – South Australia.

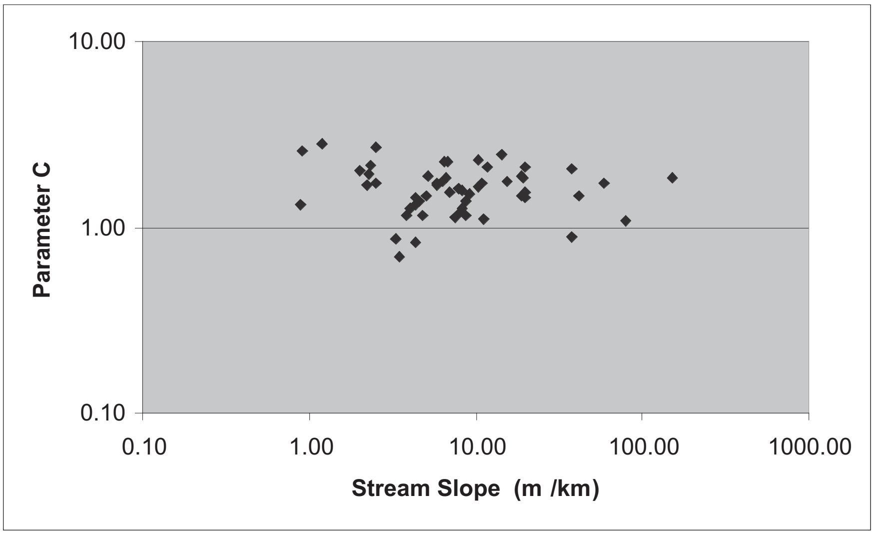

Figure 8: Parameter C versus equal area stream slope – all 54 catchments.

5 DISCUSSION OF RESULTS

5.1 Lag time and catchment area

Equations (1) and (2) indicate that the lag time or travel time of surface runoff is proportional to the catchment area raised to a power near to 0.57. Other runoff routing models have similar area terms for lag time. RAFTS and URBS have powers of 0.52 and 0.50 respectively in their lag equations. Relations between the k_c parameter and catchment area for the RORB model have powers ranging from 0.45 to 0.67, with an average near to 0.54 [Book 5 section 3.6.2 of Australian Rainfall and Runoff, 1997).

It is significant that many studies have found that stream length is related to catchment area in a very similar form to the lag-area relation [Hack 1957; Gray 1961; Mueller 1973]. For 250 catchments (0.03 to 8,000,000 km^2), for example Mueller [1973] obtained:

$$L = 1.64\,A^{0.55} \tag{3}$$

Combining data from the present study (54 catchments) with data from Brown [1973, 1980], Baron et al. [1980] and McDermott and Pilgrim [1982]produces a very similar relation for 315 Australian catchments (0.04 to 17,900 km^2):

$$L = 1.70\,A^{0.55} \tag{4}$$

$R = 0.989$

where L is in km and A is in km^2. The data for equation (4) are plotted in figure 9.

Since both lag times and stream lengths are related to catchment area in very similar form, we can conclude that lag times at a given discharge are essentially proportional to the stream or flowpath length.

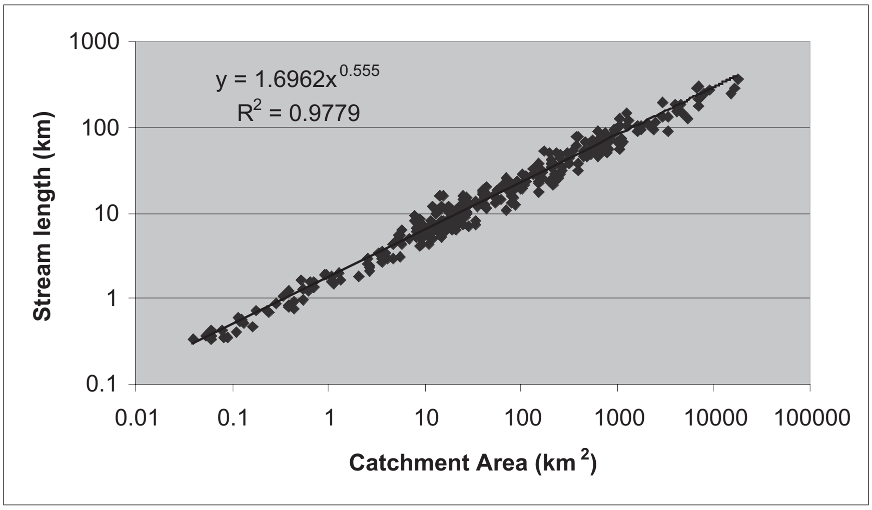

Figure 9: Stream length versus catchment area – 315 catchments in Australia.

5.2 Lag time and catchment slope

Intuitively it might be thought that catchments and streams with steeper slopes would have higher flow velocities and consequently lower lag times. This reasoning comes from Manning's equation in which velocity is proportional to slope $S^{0.5}$, indicating that travel times are proportional to $L / S^{0.5}$ and this form was used in many early equations for lag or travel time. However figures 4 to 8 indicate that slope does not have any significant effect on lag times. It is useful therefore to review the evidence linking slope to lag time. This evidence can be considered under two headings, first the changes in flow velocity in moving along the stream from headwater to the outlet within a particular catchment, and secondly changes in lag times between different catchments having different slopes.

5.2.1 Changes in flow velocity within a catchment

Extensive studies of hydraulic geometry in streams by, for example Leopold and Maddock [1953], Leopold et al. [1964] and Park [1977] have related changes in velocity in the downstream direction to discharge in the form:

$$V = a\, Q_f^{\,b} \tag{5}$$

where Q_f is the discharge at various points along the stream having the same frequency. This is commonly taken as the mean annual flow or the bankfull discharge. Typical values of b range from 0.1 to 0.2, indicating that velocities are relatively constant or increase slightly in the downstream direction. Park [1977] has noted that while some studies show decreases in the downstream direction, others show increases, and overall most streams show slight increases in the downstream direction.

Pilgrim [1976; 1977; 1982] used radioactive tracing to measure travel times on the 0.4 km^2 Research Creek catchment (214330) and found that velocities remained essentially constant in a downstream direction. A review by Pilgrim [1977] of these hydraulic geometry and radioactive tracing studies, as well as dye tracing, energy dissipation and erosional stability studies, supported the conclusion that flow velocities remain essentially constant or increase slightly in a downstream direction.

These conclusions are actually more consistent with Manning's equation than the simplistic

assumption that travel time is proportional to $L / S^{0.5}$. From Manning's equation the travel time T is :

$$T = L \,/\, V = L\, n \,/\, (R_h^{0.67}\, S^{0.5}) \tag{6}$$

In moving downstream, slope decreases, but flow depths and the hydraulic radius increase and this increase in R_h may compensate for any decrease in bed slope.

The preceding evidence clearly indicates that, rather than flow velocities decreasing in moving from the steeper headwaters to the flatter slopes near the catchment outlet, they remain essentially constant or even increase slightly in moving downstream. Consequently, lag times within a catchment are not dependent on the slope of the subcatchment or stream segment.

It is worth noting that both WBNM and most current applications of RORB allocate lag times to the subcatchments within the larger catchment using stream lengths and not stream slopes. WBNM does this through equations (1) and (2). RORB does it through its equation for lag time:

$$K_i = k_c\, (L_i \,/\, d_{av})\, Q^{1-m} \tag{7}$$

where K_i = lag time on subcatchment i, L_i = stream segment length in subcatchment i, and d_{av} =

average flowpath length for the catchment. Recent applications of RORB base d_{av} on flowpath lengths rather than other measures such as L / $S^{0.5}$ [Hansen et al. 1986; Dyer et al. 1995; Pearse et al. 2002].

5.2.2 Changes in lag time between different catchments

Many studies of lag time and of model lag parameters have found catchment area A or stream length L to be the dominant variable. The inter-changeability of L and A in these relations is not surprising since they are strongly correlated (eqs. 3 and 4). Other variables, such as catchment shape, spatial distribution of area and elevation are generally not significant. Catchment slope appears in some relations, but is generally a secondary factor. A review of catchment lag relations is given by Boyd et al. [2002].

Figures 4 to 8 for catchments in Queensland, NSW, Victoria and South Australia show that WBNM parameter C is not dependent on catchment slope. A similar lack of dependence between lag parameter k_c of the RORB model and slope is shown in many regional relations presented in Australian Rainfall and Runoff [1997], as discussed below.

For Queensland, Weeks and Stewart [1978], Morris [1982], Hairsine et al. [1983], Weeks [1986] and Titmarsh and Cordery [1991] developed relations between k_c and A alone.

Weeks [1986] also investigated possible variations of k_c within the various regions of the study, and also any effects of catchment slope, but no relations were found.

For NSW Kleemola [1987], Sobinoff et al. [1983] and Walsh and Pilgrim [1993] related k_c to A alone. Sobinoff et al. [1983] found that addition of slope to the regressions did not improve them appreciably. Walsh and Pilgrim [1993] derived relations for 46 catchments (0.1 to 13,000 km^2) between k_c and A, L and L / $S^{0.5}$. The fit of these various relations to the data were similar, and a relation involving area A was considered to be the most logical one to adopt.

For Victoria Morris [1982] and Hansen, Reed and Weinmann [1986] derived relations beyween k_c and A alone. Hansen et al. [1986] derived relations for 40 catchments (20 to 3910 km^2) using A, L, S, average flow distance d_{av}, as well as the combinations L / $S^{0.5}$ and d_{av} / L. Generally, regressions involving area A were satisfactory, with the addition of other variables giving little improvement.

For South Australia Lipp [Book 5 IEAust 1997], Maguire et al. [1986] and Kemp [1993] derived relations between k_c and A alone.

For Western Australia Weeks and Stewart [1978] and Morris [1982] derived relations between k_c and A alone. Flavell et al. [1983] derived relations for 52 catchments (5 to 6526 km^2). Generally, regressions involving stream length L were better than those using area A. For the south west k_c was related to L alone, but for the wheatbelt k_c was related to both L and S.

For the Northern Territory the Department of Mines and Energy [Australian Rainfall and Runoff 1997] k_c was related to both A and S in the humid zone, but for the transition zone between humid and arid, k_c was related to A alone.

For Tasmania Morris [1982] and the Tasmanian Hydro Electric Commission [Australian Rainfall and Runoff 1997] derived relations between k_c and A alone.

These regional relations are summarised in Australian Rainfall and Runoff [1997] Book 5, section 3.6.2. It is noteworthy that slope S appears in only two relations for all of these regions of Australia.

Dyer et al. [1995] developed regression relations between k_c / d_{av} and a range of catchment, climatic and RORB model properties for 7 groups covering the east coast of Australia, Tasmania, the Adelaide Hills, and the south west of Western Australia. A total of 72 catchments were used. Slope appeared in the equation for only one group out of seven.

One Australian study in which lag was found to be related to slope was that of Aitken [1975] for 6 catchments. This has been incorporated into the RAFTS model lag parameter B:

$$B = 0.285\ A^{0.52}\ (1+U)^{-1.97}\ S^{-0.50} \tag{8}$$

Considering all of the preceding regional relations for WBNM and RORB, slope is seen to be of only minor, or no significance in affecting catchment lag.

It is instructive to consider how Manning's equation may apply to stream reaches on different catchments, rather than to changes in velocity along the stream, as discussed in the section 5.2.1 It could be argued that steeper stream reaches will affect only the slope term in equation (6), with all other terms remaining unchanged, so that flow velocities will be higher and lag times lower. However, this is not so. Figure 10 shows values of n calculated from stream gauging data for 61 streams in the USA [Barnes, 1967] and for 78 streams in New Zealand [Hicks & Mason 1991]. Equations (9), (10) and (11) show the fitted equations, together with the correlation coefficients. The index of stream slope S_w is calculated from the fall in water level over the reach length. The NZ data contains several measurements for each reach, with slightly different values of n and S_w. The single pair of n and S_w values which were representative for each reach were selected for the present study.

USA

$$n = 0.0388\ S_w^{\ 0.124} \tag{9}$$

R = 0.57

NZ

$n = 0.0426\ S_w^{\ 0.249}$ (10)

R = 0.60

ALL

$n = 0.0405\ S_w^{\ 0.191}$ (11)

R = 0.55

Although there is quite a bit of scatter and the correlation coefficients are not high, there are clear trends for higher roughness coefficients on catchments with steeper stream reaches. Thus the higher values of *S* will be partly compensated by the higher values of *n*, so that travel times may not be greatly affected by catchment or stream slope.

6 A LINK BETWEEN THE LAG PARAMETERS OF WBNM, RORB, URBS AND RAFTS

The regional relations discussed in the previous section all show that the lag parameter k_c of RORB is strongly correlated with catchment area *A* raised to a power slightly greater than 0.5. Since stream lengths are also strongly related to catchment area (eqs. 3, 4) raised to a very similar power, it follows that k_c will be related to stream length or a measure of stream length. One measure of stream length which has been adopted in RORB is the average flow distance d_{av}. Using the data of Hansen et al. [1986] for 30 catchments (20 to 3910 km^2) a relation between d_{av} (km) and *A* (km^2) is :

$d_{av} = 0.98\ A^{0.54}$ (12)

R = 0.923

McMahon and Muller [1983, 1986] and Yu [1990] have used these relations to form an area-standardised lag parameter k_c / d_{av}. Kemp [1993] formed a similar area-standardised lag parameter $k_c / A^{0.57}$. Because of the strong relation between k_c and measures of area and stream length, the area-standardised lag parameter should be essentially independent of the catchment size. The area-standardised lag parameter in RORB can then be seen as analogous to lag parameters *C* (eq. 1), *B* (eq. 8) and β (eq. 13) in the WBNM, RAFTS and URBS models respectively, since these three models already include area *A* in their lag equations.

$$S_{catch} = \beta \left\{ \frac{A^{0.5}(1+F)^2}{(1+U)^2} \right\} Q^m \qquad (13)$$

Yu [1990] studied the value of k_c / d_{av} for 122 catchments in Victoria, Western Australia, New South Wales, Queensland and the Northern Territory (41 catchments in total). The average value of k_c / d_{av} was found to be 1.09. Pearse et al. [2002] combined the data of Hansen et al. [1986], Dyer et al. [1995] and Yu [1990], for more than 220 catchments in Queensland, New South Wales, Victoria, Tasmania and Western Australia. The mean value of k_c / d_{av} was found to range between 0.96 and 1.25.

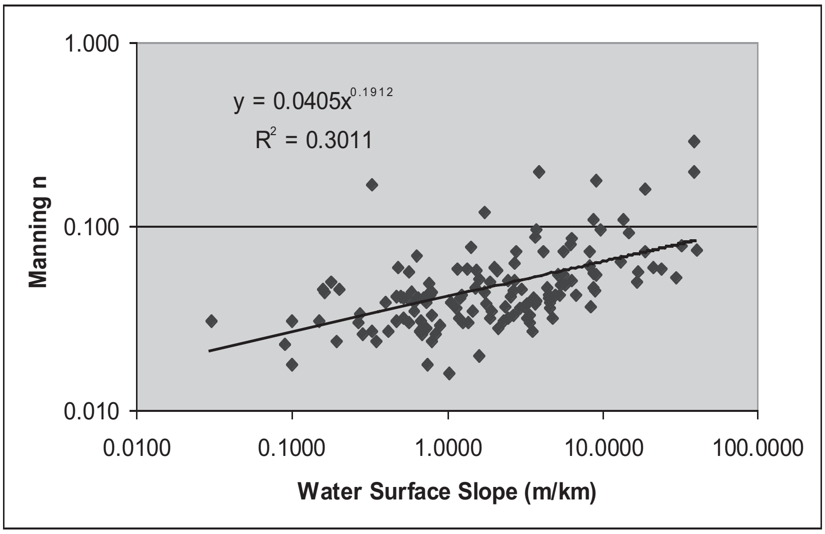

Figure 10: Relation between Manning n and stream slope – 139 catchments in USA and NZ.

It could be expected that the area-standardised parameters of RORB, WBNM, RAFTS and URBS are related to one another. Considering equations (1) and (7) for example, reveals that $CA_i^{0.57}$ in WBNM corresponds to L_i (k_c / d_{av}) in RORB as long as the nonlinearity parameters *m* are similar. In RORB a commonly used value of *m* is 0.8, very close to 0.77 in WBNM.

The terms A_i and L_i refer to subcatchment areas and stream segment lengths rather than to the total catchment areas and stream lengths used in equations (3) and (4). Boyd [1976] plotted data for 62 subcatchments of 5 catchments near Sydney

(0.04 to 90 km^2) and found that the data closely fitted equation (4). Replacing L_i by equation (4) in the above relation gives $CA_i^{0.57} = 1.70\ A_i^{0.55}\ (k_c\ /\ d_{av})$, which is close to $C = 1.70\ (k_c\ /\ d_{av})$.

Although the form of this theoretical relation is valid, the coefficient 1.70 is not strictly correct for several reasons. One is that flood routing in RORB occurs between nodes at subcatchment centroids whereas WBNM performs routing within subcatchments. Additionally, RORB routes combined rainfall-runoff and upstream runoff, whereas WBNM routes these components separately. These different approaches to routing mean that the coefficient will not be equal to 1.70. A better estimate of the relation between the models is to compare average values of C and $k_c\ /\ d_{av}$. These are 1.59 (section 5.2) and 1.10 (mid-range between 0.96 and 1.25), giving :

$$C = 1.45\ (k_c\ /\ d_{av}) \qquad (14)$$

Similar analysis indicates that parameter β of URBS (eq. 13) should be also be proportional to $k_c\ /\ d_{av}$. For RAFTS the proportionality coefficient of eq. (8) should also be related to $k_c\ /\ d_{av}$ but with an adjustment required for the slope term S.

It should be noted that the correspondence between the area-standardised lag parameters of the various models depends slightly on the power to which area A is raised, as well as the nonlinearity parameter m, however these are not too dissimilar in the four models. The particular ratio between the parameters will depend on the way in which the lag parameter is incorporated into flood routing in the particular models, as well as the method adopted for stream channel routing. The ratio 1.45 between RORB and WBNM will not apply to RAFTS and URBS.

7 CONCLUSIONS

The lag parameter C of the runoff routing model WBNM has been derived from recorded storm data on 54 catchments in Queensland, NSW, Victoria and South Australia. Parameter C was found to be independent of the flood size, indicating that the nonlinearity parameter m = 0.77 used in WBNM adequately describes catchment nonlinearity for these events. Parameter C was also found to be independent of catchment area. These results show that the lag relations in WBNM (eqs. 1 and 2) correctly allocate lag times within the model.

Plots of parameter C against equal area stream slope showed a slight trend for C to decrease in steeper catchments in Queensland, but no trends were apparent for the other states of Australia. Overall, there was no strong trend for C to vary with catchment slope, over a wide range of slopes, from 0.9 to 150 m/km. This indicates that the lag equations used in WBNM (eqs. 1 and 2) adequately allocate lag times. These results are in accord with many published relations for the RORB runoff routing model. A review of studies on the variation of flow velocity within catchments, and the variation of lag times between different catchments, supports these results.

The most widely used runoff routing models in Australia, RORB, WBNM, RAFTS and URBS all use area-standardised lag parameters, and these can be shown to be related to one another. In particular, there is a direct relation between parameter C in WBNM and $k_c\ /\ d_{av}$ in RORB.

From the study in these states of Australia, a value of C = 1.6 is recommended as a guide for applying WBNM to ungauged catchments.

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Table 1:
Details of catchments and storm events.

River	Location	NSN	Area (km²)	Stream L (km)	Stream Slope (m/km)	Sub catchts	Events	Max peak (m³/s)	C mean
North Johnstone	Tung Oil	112004	930	85.8	7.60	56	21	3727	1.12
South Johnstone	Central Mill	112101	390	78.2	8.80	46	20	2077	1.37
North Johnstone	Nerada	112905	808	73.2	8.70	46	20	2848	1.16
Herbert R	Gleneagle	116004	5370	128	2.00	91	9	3671	2.03
Wild R	Silver Valley	116014	585	55.8	5.80	96	14	1346	1.71
Herbert R	Zattas	116905	7292	226	4.00	140	7	4540	1.25
Herbert R	Nashs Crossing	116907	6842	214	4.30	119	14	4273	1.44
Haughton R	Powerline	119003	1735	94.5	2.50	119	7	3031	1.71
Haughton R	Mt Piccaninny	119005	1139	68.1	3.80	84	12	2270	1.16
Don R	Ida Ck	121001	620	46.3	4.30	53	15	2333	0.83
Don R	Reeves	121003	1010	66.7	3.30	96	12	3480	0.86
Don R	Mt Dangar	121903	808	55.6	3.50	77	8	1901	0.70
Six Mile Ck	Cooran	138107	164	31.6	1.20	37	11	559	2.79
Mary R	Bellbird ck	138110	479	46.3	4.80	31	10	1258	1.16
Mary R	Moy Pocket	138111	830	69	2.20	34	10	3194	1.68
Kandanga Ck	Hygait	138113	176	52.5	5.10	25	9	353	1.46
Mary R	Gympie	138900	2919	131	0.90	29	8	6212	2.55
Blicks R	Dundurrabin	204020	251	43	19.00	16	9	481	1.46
Blicks R	Hernani	204021	70	22.8	11.00	16	8	337	1.72
Bobo R	Nursery	204026	80	22.5	6.25	19	9	144	1.78
First Ck	Pokolbin 1	210063	14.3	15.6	5.23	12	6	13.9	1.88
Pokolbin	Pokolbin 3	210068	25.2	14.6	6.70	21	8	19.3	1.84
Kowmung R	Cedar Ford	212260	733	85.4	7.95	31	4	1250	1.60
Coxs R	Lidsdale 9	212309	0.24	0.70	37.9	5	5	0.45	2.04
South Ck	Mulgoa Rd	212320	89	22.9	2.27	17	18	119	1.92
Eastern Ck	Bridge	212340	24.9	9.34	5.83	12	17	89	1.67
O'Hares Ck	Wedderburn	213200	73.4	21.4	10.33	27	5	452	1.64
Macquarier Rt	Albion Park	214003	35	11.8	38.0	16	7	399	0.89
Kellys Ck	Weir	214311	2.54	2.5	19.60	7	12	22.5	1.56
Research Ck	Research Ck	214330	0.39	0.8	58.9	7	18	3.23	1.72
Cawleys Ck	Lower Cawleys	214334	5.52	5.47	41.3	15	19	30	1.48
Hacking R	Upper causeway	214340	40.2	17.9	9.28	15	17	119	1.50
Stony Ck	Illawarra		3.57	2.64	152	9	18	78	1.85
Shoalhaven R	Nowra Bridge	215401	6910	305	8.33	43	7	9795	1.58
Deua R	Wamban	217002	1230	143	2.55	34	6	2485	2.70
Cobbannah Ck	near Bairnsdale	224209	103.6	28.8	14.4	20	8	66	2.48
Latrobe R	near Noojee	226222	62.2	14.3	10.3	21	6	8	2.32
East Tarwin R	Mirboo	227228	44.3	11.5	6.85	15	10	22	2.27
Ettersglen Ck	Ettercon No.1	229136	0.12	0.55	80	1	17	0.027	1.09
Lerderderg R	Sardine Ck	231213	153	22.8	11.9	46	9	176	2.09
Warrambine Ck	Warrambine	233223	57.2	14.5	8.21	15	9	58	1.27
Murray R	Biggara	401012	1238	106	6.43	16	10	182	2.26
Wanalta Ck	Wanalta	405229	108.8	21.2	2.36	25	10	61	2.15
Seven Cks	Polly McQuinns	405234	153	36.9	0.882	15	10	47	1.31
Spring Ck	Fawcett	405261	62.6	20.5	11.1	16	12	21	1.11

River	Location	NSN	Area (km^2)	Stream L (km)	Stream Slope (m/km)	Sub catchts	Events	Max peak (m^3/s)	C mean
Avon R	Beazleys Bridge	415224	259	27.8	4.4	15	13	103	1.31
Scott Ck	Scotts Bottom	503502	26.8	10.0	19.5	28	9	15.2	1.83
Echunga Ck	US Mt Bold Res	503506	34.2	13.5	4.60	23	10	43	1.38
Lenswwod Ck	Lenswood	503507	16.5	6.7	18.7	17	8	15	1.90
Inverbrackie Ck	Craigbank	503508	8.4	6.1	15.6	11	7	17.2	1.76
Onkaparinga R	Western Branch	503541	24.2	8.8	19.9	16	8	14.7	1.44
Torrens R	Mt Pleasant	504512	26.0	9.0	7.00	18	11	66	1.55
Sixth Ck	Castambul	504523	44.0	16.8	19.7	35	9	73	2.09
Onkaparinga R	Woodside	503538	51.9	15.5	8.10	21	8	51	1.20

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Michael graduated in Civil Engineering from the University of New South Wales in 1977, and subsequently went to the University of Wollongong, where he is currently Associate Professor in the Faculty of Engineering.

His research interests are flood hydrology, urban stormwater management, and water resources, and he has published more than 80 papers in these areas. His research into flood hydrograph modeling, flood frequency analysis, flood detention basin design, and culvert hydraulics is referenced in the Engineers Australia Guide to Flood Estimation, Australian Rainfall and Runoff (1987, 1997).

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