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The effects of urbanisation on hydrologic response: a study of two coastal catchments

L. F. Watts[1] and R. M. Hawke

School of Earth Sciences, Victoria University of Wellington, New Zealand

[1] *now at Greater Wellington Regional Council*

Abstract

Coastal areas with low topographic relief have long been problematic for determining hydrologic response at the catchment scale, and there is little guidance for estimating their hydrologic model parameters. This study provides observational results to improve runoff modelling of small New Zealand coastal catchments. Two rapidly urbanising coastal catchments were studied: Mazengarb Stream catchment (Paraparaumu) and a small catchment in Papamoa (Tauranga). Flows were monitored for 8 to 12 months in four subcatchments within each catchment. The subcatchments were small (less than 3.5 km^2) and ranged in land use from rural to dense residential. The hydrologic events monitored were all of a relatively high frequency and low-magnitude.

The Rational Method is commonly used for estimating peak discharge from ungauged catchments, which include the majority of urbanised drainage networks. This method uses a runoff coefficient to model peak storm flow using catchment characteristics and rainfall data. However, estimating this coefficient is a major source of uncertainty, and current guidelines are generally based on overseas work. The measured rainfall-runoff response showed that:

- Median runoff coefficients for the urban areas (0.18-0.23) of both catchments were significantly greater than those for the rural and low-density residential/rural areas (0.05-0.08), and
- the runoff coefficient was related to the percentage of impervious cover in a subcatchment.

The U.S. Soil Conservation Service method uses the dimensionless "curve number". Curve numbers derived for the study areas showed that:

- the intra-subcatchment variability in curve number could be linked to event characteristics;
- subcatchments with similar land uses generally produced statistically similar curve numbers;
- median curve numbers for the urban areas (76-88) were significantly higher than those for the rural and low-density residential/rural areas (55-59); and
- the curve number was related to the percentage of impervious cover in a subcatchment.

Overall, the study areas showed a strong correlation between land use and hydrologic response. The change from rural to residential land use resulted in baseflow becoming negligible, a significant decrease in the time of rise, peak flow increasing by 300-900%, and significant changes in the runoff coefficient and curve number. The results from the two locations were statistically

similar and the parameters derived could be related to catchment characteristics, so the results provide a basis for predicting the effect of urbanisation on high-frequency hydrologic response for small New Zealand coastal catchments.

Introduction

Catchments in coastal regions of New Zealand often have permeable soils and low-gradient drainage systems, with mixed rural and urban land use following the drainage of peat swamps. These areas of low relief have long been problematic for determining hydrologic response at the catchment scale (Sheridan *et al.*, 2002). Many coastal catchments are also undergoing rapid urbanisation at present. There has been considerable research in New Zealand into rainfall-runoff processes in undisturbed hill-country catchments (for example Hayward, 1976; Mosley, 1979; Pearce and McKerchar, 1979; Taylor and Pearce, 1982) and into the effects of urbanisation on hydrologic response (for example Williams, 1976; Martell, 1996; Ward, 1997; Tomlinson, 1998); however, there have been few studies directly related to the effects of urbanisation on runoff in low-relief coastal areas.

Urbanisation alters the physical hydrology of a catchment through many processes. Removal of vegetation, allows more rainfall to reach the ground, and draining of swamps reduces the natural water storage in the catchment. The increase in impervious surfaces cause water to runoff more quickly and in greater volumes, and the increase in channels and pipes conveying stormwater increases the drainage density of the catchment, leading to shorter times of concentration. Artificial channelisation increases the velocity of flow, and subdivision earthworks may alter subcatchment boundaries. The cumulative effect of these processes is a marked change in the storm hydrograph and a decrease in baseflow in urban catchments. Floods peak more rapidly, with peaks of greater magnitude than those of undeveloped areas. In addition, floods occur more frequently, with the catchment being more sensitive to brief, high-intensity rainfall from small- to moderate-sized storms (McConchie, 1992; O'Loughlin *et al.*, 1996).

Modelling rainfall-runoff processes is necessary to determine peak flows and runoff volumes likely to occur in a catchment, and is thus vital for the design of effective stormwater systems and flood protection measures. There is a need for improved runoff modelling of low relief coastal areas, particularly for stormwater system design; therefore this study focuses on two coastal areas. This study seeks to:

- determine the effect of urban development on the magnitude and timing of hydrologic response through direct measurement,
- use this information to derive values for commonly used hydrologic model runoff
- comment on the potential for deriving regional relationships for estimating runoff parameters for the New Zealand coastal zone.

In this paper, empirical data and two modelling approaches are used: the Rational Method to estimate peak flow (O'Loughlin and Robinson, 1987) and the United States Soil Conservation Service (1986) (SCS) method to predict total runoff volume. The SCS method, often used as a loss model in unit hydrograph applications, is particularly useful as it relies largely on one parameter, the curve number. However, previous studies have commonly used curve number values estimated in the United States. Despite the lack of New Zealand data and testing, recent work has used the SCS method in unit hydrograph applications, because the method is often incorporated into computer programs designed for use by stormwater engineers, such as HEC-1 (for example, Auckland Regional Council, 1999; Beca Carter Hollings & Ferner Ltd, 1999a; Connell-Wagner 1992, 2000). After deriving the appropriate curve number values, Watts (2002) applies and tests these with unit hydrographs. This work will be the subject of a later paper.

Study area

Two catchments were chosen for study: a small drainage system in Papamoa (Tauranga) and the Mazengarb Stream catchment in Paraparaumu (Kapiti Coast). This allowed the comparison of results from coastal zones in different regions of New Zealand.

The Mazengarb catchment (approximately 8.7 km^2) lies within the Paraparaumu urban area. This coastal area is relatively narrow (4 km wide) and dominated by residential, commercial and "under-developed" areas. Before urbanisation, Paraparaumu consisted of sand dunes and inter-dune peat swamp (Baldwin, 1993). Small streams from the foothills terminated in the swamp areas and generally lacked the ability to break through the sand dunes and flow out to the sea. Development resulted in the removal of flood storage capacity. The Mazengarb Stream has been modified in many places and receives stormwater from numerous pipes, as well as effluent from the Paraparaumu wastewater treatment plant.

The Papamoa urban area lies behind coastal sand hills and, as in the case of Paraparaumu, prior to development the land consisted of easy-rolling sand dunes and swampy areas. When the land in western Papamoa was drained for farming, a cutting through the sandhills was made to channel runoff to the sea (Harrisons Cut). While flow through this was reported as infrequent (Murray-North Partners, 1976), flow from urbanising areas of Papamoa West (2.3 km^2) is now diverted through this cutting and is perennial.

Study approach

A major source of uncertainty in hydrological estimates is informational uncertainty (Edwards and Haan, 1990), which arises in part from natural variations in parameter values and the derivation of parameters from limited datasets. There are essentially two methods for deriving parameters for rainfall-runoff modelling: the deterministic approach, in which parameters are calculated from data for actual events, or the probabilistic interpretation of rainfall-runoff data. The probabilistic approach has considerable merit (Titmarsh *et al*, 1995), but it is difficult to apply to New Zealand coastal urbanising catchments because it requires long records of rainfall and runoff. Stormwater design and runoff estimation is common for the subcatchment scale, hence this study takes the deterministic approach and measures the runoff response from subcatchments with various land use characteristics, and uses this data to derive parameter values at this scale.

For a regionally calibrated method, guidelines are needed for selecting the parameter value. This is easiest if the parameter can be related to a physically-based quantity, such as a catchment characteristic. This study's deterministic approach and results allows comments to be made on the viability of developing regional relationships for estimating runoff parameters for the New Zealand coastal zone.

Within each of the Mazengarb and Papamoa catchments four subcatchments were selected for continuous monitoring. Land use within the subcatchments ranged from predominantly rural to residential (Table 1 and Figure 1). The percentage of impervious cover within each subcatchment was estimated from recent aerial photographs. Although the percentage of impervious cover seems high for Realm Drive and Rosewood (relative to the "normal" amount of impervious cover in a residential catchment), these two subcatchments are very small and roads make up a considerable proportion of the land area. The Ratanui subcatchment is referred to as "low-density residential", as its percentage of impervious cover was significantly lower than that of the other residential subcatchments. The other residential subcatchments are referred to as "dense residential" to distinguish them from the Ratanui subcatchment.

At each subcatchment outlet an ISD™ or Druck™ pressure transducer, coupled to a Campbell Scientific™ CR10 datalogger, was used to record stage height every five minutes. Following calibration in the laboratory, the transducers were bolted to the culvert or pipe base. Calibration was checked by manually measuring water levels with staff gauges. For each site a rating curve was developed by manually determining the discharge, using a small Ott current meter, at several stage heights. This level of hydrometric control allowed the derivation of high quality flow data (Table 2).

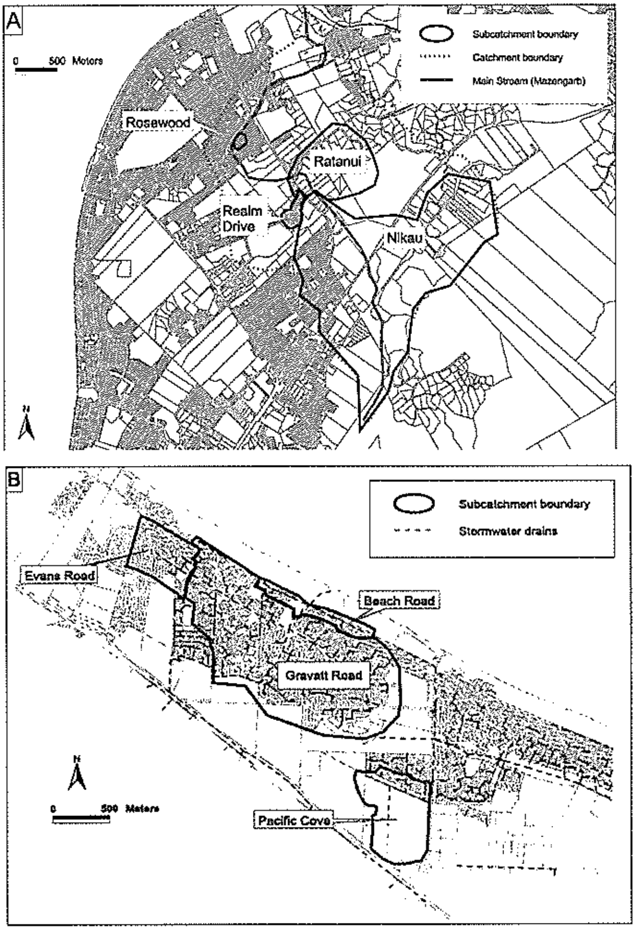

Figure 1 – The two study areas include eight subcatchments:
A. Mazengarb catchment (Rosewood, Ratanui, Realm Drive and Nikau subcatchments). B. Papamoa West catchment (Evans, Gravatt Road, Beach Road and Pacific Cove subcatchments). Cadastral maps courtesy of Greater Wellington Regional Council and Tauranga District Council, respectively.

Table 1 – Subcatchment characteristics

Subcatchment	Area (ha)	Percentage Impervious	Average channel slope (m/m)	Time of concentration (min)[1]	Predominant land use
Mazengarb					
Realm Drive	5.8	44	0.012	12	Dense residential
Rosewood	1.4	46	0.023	6	Dense residential
Nikau	354	7	0.006	53	Rural
Ratanui	57.9	9	0.009	25	Low-density residential
Papamoa					
Evans Road	27.3	34	0.0008	40	Dense residential
Pacific Cove	45.3	3	0.001	46	Rural
Beach Road	14.4	29	0.005	17	Dense residential
Gravatt Road	185	32	0.0009	n/a	Dense residential

[1] See results section for discussion of this parameter

Table 2 – Flow characteristics during the monitoring period

Subcatchment	Maximum flow (l/s)	Maximum specific flow (l/s/ha)
Mazengarb		
Realm Drive	172	30
Rosewood	26	19
Nikau	1348	4
Ratanui	704	12
Papamoa		
Evans Road	410	15
Pacific Cove	373	8
Beach Road	465	32

Note: Maximum flow at Gravatt Road (Papamoa) not reported; flow is delayed through a pond system in this subcatchment, therefore the measured peak flow is not a true reflection of hydrologic response.

Automatic tipping-bucket raingauges (0.2 mm resolution) were installed within each catchment. Unfortunately, due to repeated vandalism and occasional equipment failure, rainfall data is available from only one gauge per catchment at times. Over the course of the monitoring period (2001) approximately 880 and 700 mm of rain fell in the Mazengarb and Papamoa catchments respectively. Seven "significant events" (rainfall of at least 20 mm within a 24-hour period) for the Mazengarb and eight for the Papamoa catchments could be used for parameter determination (Table 3).

Depth-duration-frequency tables were obtained for the two catchments (Harkness, 2002; Opus, 2000). All the rainfall events recorded for the Mazengarb catchment were of less than a 2-year return period, with the exception of the rainfall event beginning on November 21, which had a return period of between 2 and 5 years for both the 24- and 48-hour durations. All rainfall events observed in the Papamoa catchment had return periods of less than 2.33 years.

Results

Hydrologic response

1. Baseflow

To compare the storm flow from each subcatchment, baseflow needed to be removed from the total measured flow. Conceptually this is easy—just remove the flow that is not due to surface runoff (Bedient and Huber, 1992). In practice however it is

Table 3 – Characteristics of rainfall events during the monitoring period

Catchment	Event start date	Total rain (mm)[1]	Maximum rainfall intensity (mm/hour)[2]	Approximate duration of rainfall (hours)[3]
Mazengarb	28 July	40	22	4
	23 August	59	39	35
	6 October	41	11	19
	31 October	30	16	8
	13 November	49	22	27
	21 November	80	14	39
	8 December	37	9	31
Papamoa	4 September	24	9	5
	15 September	29	23	11
	9 October	32	21	21
	22 November	56	34	13
	8 December	43	13	17
	18 December	58	35	12
	19 December	27	29	5
	27 December	20	40	3

[1] Average of totals from all raingauges

[2] Maximum intensity of event during a 20-minute duration

[3] May include several rainfall bursts

arbitrary, as there is no universally accepted procedure for removing baseflow. The event hydrographs were analysed and, following field verification, it was concluded that any flow in the channel 24 hours after rainfall ceased was baseflow. This was then removed from the total measured flow.

This study was concerned with surface runoff (stormflow), and did not investigate the effect of urbanisation on baseflow. However, when baseflow was removed, it was apparent that only the rural and low-density residential subcatchments had a significant baseflow component. Thus development in the dense residential subcatchments had resulted in baseflow becoming either absent or negligible in both coastal areas. Figure 2 shows an example of flow measured during an event in the Mazengarb catchment (prior to baseflow removal), showing the lack of baseflow in the Realm Drive subcatchment, compared to that in the rural Nikau subcatchment, immediately following the cessation of the event.

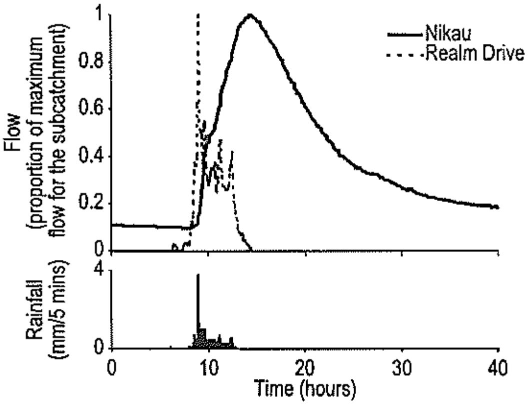

Figure 2 – Measured flow at two subcatchments in the Mazengarb catchment (July event) showing difference in baseflow contribution

2. Stormflow

The specific discharge hydrographs (Fig. 3) from the subcatchments display the differences in peak runoff and in the temporal pattern of runoff.

In the Mazengarb catchment, for all events, peak specific discharge was greater (on average by 900%) for the residential subcatchments of Rosewood and Realm Drive than for the rural Nikau subcatchment. In addition, the peak specific discharge from the low-density residential Ratanui subcatchment was greater (by 150 to 200%) than that from the Nikau subcatchment. The responsiveness of the flow to changes in rainfall intensity also increases with increasing urbanisation (Fig. 3). The pattern of response from the Papamoa subcatchments is similar (Fig. 4).

For all events, peak specific discharges from the urbanised subcatchments of Evans Road and Beach Road were greater, on average by 300% greater, than those from the rural Pacific Cove subcatchment. The larger increase in peak flow with urbanisation in the Mazengarb Catchment (900% compared to 300% in Papamoa) could be because the Papamoa stormwater network is wide, low-sloped swales, compared to the incised channels and pipes in the Mazengarb catchment. Thus the Papamoa stormwater network design may provide for some loss. However, it is difficult to directly compare the catchments' responses, as no large magnitude events were observed. Overall, in both areas, the increase in urbanisation resulted in shorter, more peaked runoff, shorter time to peak flow and more rapid recession rates, a greater peak specific discharge, and a decline in the contribution from baseflow.

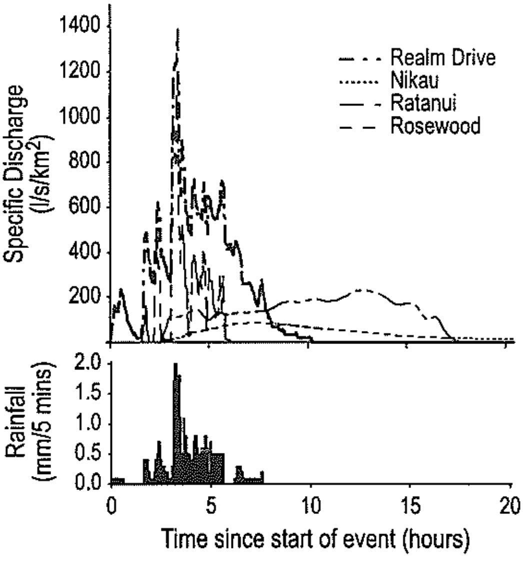

Figure 3 – Specific discharge hydrographs for the Mazengarb subcatchments (November 14 event)

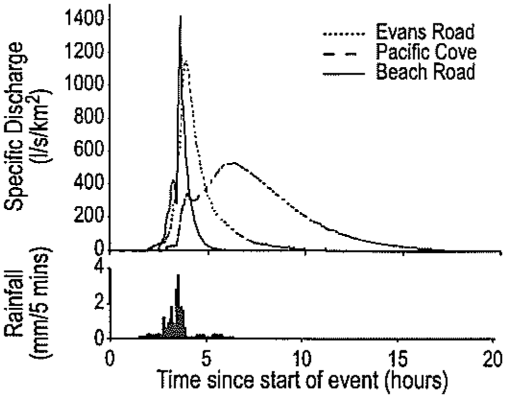

Figure 4 – Specific discharge hydrographs for the Papamoa subcatchments (December 19 event)

Rational Method

To be more applicable to stormwater system design and management, it is necessary to be able to model this change in response and calibrate the appropriate model parameters. The Rational Method is the best-known simple model for estimating peak flow for stormwater system design (O'Loughlin and Robinson, 1987). The peak flow at the catchment outlet is computed as a function of the catchment area, a runoff coefficient, and the rainfall intensity (Equation 1). While it may be overly simplistic, especially because of the rather arbitrary determination of the runoff coefficient, this method allows the peak flow to be calculated in the absence of flow data. Within well-recognised limitations, such as restrictions on catchment area, it is suitable for peak flow estimation (New Zealand Institute of Engineers, 1980; Singh, 1992).

Equation 1 The Rational Method

$$Q_p = 0.278\ CIA$$

where

Q_p = peak flow (m^3/s)
C = the runoff coefficient
I = rainfall intensity for a duration equal to the time of concentration (mm/hr)
A = catchment area (km^2)

Several publications have tables of runoff coefficients for various land uses, such as the New Zealand Building Code Approved Documents (Table 4; Building Industry Authority, 1995). Such published values are useful when there are no long-term flow records for the catchment. However, the estimates are from overseas: the values in Pilgrim and Cordery (1993) are those recommended by the American Society of Civil Engineers and the United States Water Pollution Control Federation, while the New Zealand Institute of Engineers (1980) and Building Industry Authority (1995) present the same table of values, which were derived from Australian and American data (Anderson, 1977). Given the runoff coefficient is the ratio of the peak rate of runoff to the peak rainfall, and so is an indication of runoff potential (O'Loughlin and Robinson, 1987), it seems unlikely that values determined overseas will model New Zealand conditions well. Given the catchment characteristics and high quality flow and rainfall data, it is possible to

Table 4 – Runoff coefficients recommended for use in New Zealand (from Building Industry Authority, 1995)

Description of surface	C
Natural surface types	
Bare impermeable clay	0.70
Bare uncultivated soil of medium soakage	0.60
Heavy clay soil types:	
– pasture and grass cover	0.40
– bush and scrub cover	0.35
– cultivated	0.30
Medium soakage soil types:	
– pasture and scrub cover	0.30
– bush and scrub cover	0.25
– cultivated	0.20
High soakage gravel, sandy and volcanic soil types:	
– pasture and grass cover	0.20
– bush and scrub cover	0.15
– cultivated	0.10
Parks, playgrounds and reserves:	
– mainly grassed	0.30
– predominantly bush	0.25
Gardens, lawns, etc.	0.25
Steel and non-absorbent roof surfaces	0.90
Asphalt and concrete paved surfaces	0.85
Near flat and slightly absorbent roof surfaces	0.80
Stone, brick and precast concrete paving panels:	
– with sealed joints	0.80
– with open joints	0.60
Railway and unsealed yards and similar surfaces	0.35
Land use types	
Fully roofed and / or sealed developments	0.90
Industrial, commercial, shopping areas and town house developments	0.65
Residential areas in which impervious area exceeds 35% of gross area	0.45

compute the runoff coefficient for each event and subcatchment. This allows an assessment of variations in the coefficient both between and within subcatchments.

The rainfall intensity used in the Rational Method is the maximum rainfall intensity sustained for a duration equal to the time of concentration. This is the time taken for runoff to flow from the most hydraulically remote part of the catchment to the catchment outlet (Debo and Reese, 1995). This is assumed to be an intrinsic characteristic of the catchment; however, in reality it varies between storms due to antecedent moisture conditions, rainfall distribution, and changes in the nature and number of flowpaths within the catchment (Guo, 2001; Dingman, 1994). Several empirical methods have been developed for estimating the time of concentration, with the technique being determined by the nature of the conditions. The Ramser-Kirpich method has been recommended for use in New Zealand (Building Industry Authority , 1995; Lew and Blackwood, 1995) (Equation 2).

Equation 2 Ramser-Kirpich method of determining the time of concentration

$$T_c = 0.0195\ L^{0.77}S^{-0.385}$$

where

T_c = the time of concentration (min)

L = flow length (m)

S = average slope (m/m)

This method was developed for small rural catchments in the United States with low slopes (3-10%) (McCuen, 1998) and so was used for the rural and less developed subcatchments in this study. For the urbanised subcatchments the Kerby equation was used, since this equation was developed for small low-angle urban catchments (Equation 3).

Equation 3 Kerby method of determining the time of concentration

$$T_c = 1.44(nLS^{-0.5})^{0.467}$$

where

T_c = the time of concentration (min)

n = a roughness coefficient

L = flow length (m)

S = average channel slope (m/m)

As a check of the computed time of concentration values (Table 1), the computed values were converted to velocities (by dividing main stream length by the time of concentration) (after Davidson Ayson, 1996). In all cases the computed values appeared appropriate. Once the time of concentration was determined for each subcatchment, the maximum rainfall intensity for this duration was determined for each event. Thus for each event (Table 3), for each subcatchment, the runoff coefficient was determined (Fig. 5).

For each subcatchment there was considerable variation in the runoff coefficient. This is consistent with other studies that have used actual storm data. This intra-subcatchment variation has previously been explained by antecedent moisture conditions,

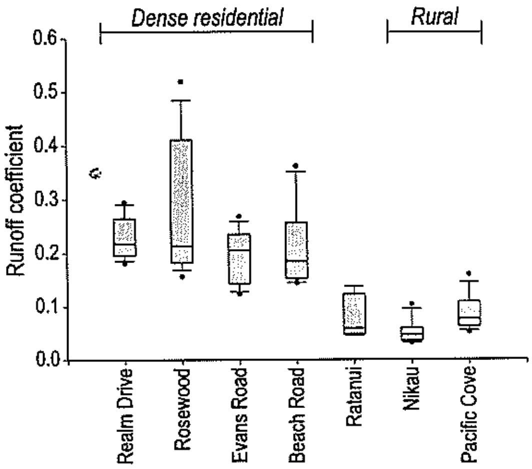

Figure 5 – Runoff coefficients derived for the study subcatchments

storm duration, storm intensity, and/or total rainfall volume (Bedient and Huber, 1992; New Zealand Institute of Engineers, 1980). For each subcatchment, regression analysis was used to explain the observed variation. For most subcatchments the runoff coefficient was positively correlated with rainfall depth, total runoff depth, or both (i.e. storm magnitude). This is consistent with previous studies (e.g. Pilgrim, 1982; Titmarsh *et al.*, 1995). During less frequent (larger) events infiltration and other losses have a smaller effect; hence the runoff coefficient is higher (Debo and Reese, 1995). However, the coefficients of determination were usually low, and in some cases the relationship was controlled by one value, probably because of the relatively small number of events available for analysis, and the fact that all events were of low magnitude.

Given the observed intra-subcatchment variation, and the small datasets, a two-sample Kolmogorov-Smirnov test (see Zar, 1999) was performed to assess inter-subcatchment variation (Fig. 5). While the results from the Papamoa and the Mazengarb catchment were derived from different events, the catchments have similar topography and the events were similar (i.e. relatively high frequency and low magnitude). This statistical comparison showed that:

1. all dense residential subcatchments (Realm Drive, Rosewood, Evans Road and Beach Road) had statistically similar runoff coefficient values;
2. the runoff coefficients for the Ratanui subcatchment (low-density residential land use) were statistically similar to those from the rural Nikau and Pacific Cove subcatchments;
3. the runoff coefficients from the Pacific Cove subcatchment were statistically greater than those of the Nikau subcatchment; and
4. all dense residential subcatchments had significantly greater runoff coefficient values than those from the Nikau, Pacific Cove and Ratanui subcatchments.

To assess inter-subcatchment variation requires the selection of a "representative" subcatchment runoff coefficient. Titmarsh *et al.* (1995) and Auckland Regional Council (1995) compare coefficients derived for the 10-year return period event. This is not possible for this study because of the nature of the events monitored. Because of the small number and range of values determined, the median values are used (Table 5).

Table 5 – Representative runoff coefficients for each subcatchment

Subcatchment	Predominant land use	Median runoff coefficient
Mazengarb Catchment		
Realm Drive	Dense residential	0.23
Rosewood	Dense residential	0.21
Nikau	Rural	0.05
Ratanui	Low-density residential	0.06
Papamoa Catchment		
Evans Road	Dense	0.21
Pacific Cove	Rural	0.08
Beach Road	Dense residential	0.18

These median values can be explained, with a high degree of confidence, by the percentage of impervious area within the subcatchment (Fig. 6; r^2=0.89 p=0.001). As the proportion of permeable area in a catchment decreases infiltration is reduced; hence, catchment losses are reduced and the runoff coefficient increases. The strength of the relationship between the percentage of impervious cover and the runoff coefficient, as has been observed in previous studies, is one reason why land cover has been proposed as a tool for selecting a suitable runoff coefficient and thus estimating the effects of urbanisation (Urbonas and Roesner, 1993; O'Loughlin and Robinson, 1987).

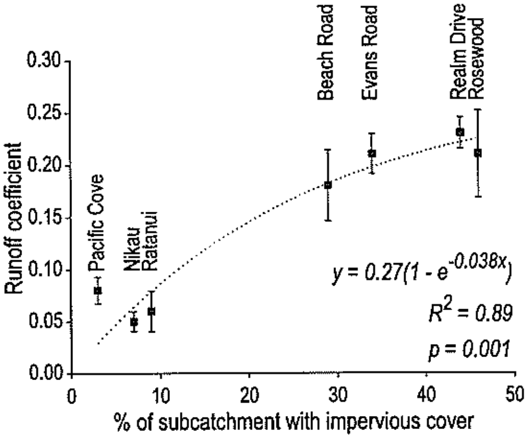

Figure 6 – The percentage of impervious cover and the median runoff coefficients.

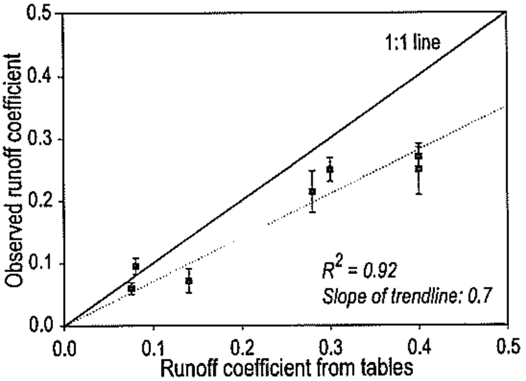

Figure 7 – A comparison of observed runoff coefficients (median values adjusted to 5-year return period) and values from conventional tables (adjusted for low slope)

Comparison of the physically determined runoff coefficients with runoff coefficients selected from tables provides an assessment of the conventional published values (Table 4). A runoff coefficient for each subcatchment was determined using the tables values (and the appropriate weighting by area). However, these conventional values assume a topographic slope of 5-10%, and so to adjust for the flatter subcatchments 0.05 was subtracted from each value (as per Building Industry Authority, 1995). Furthermore, these conventional values are for storms with a 5- to 10-year return period. Thus the measured values in Table 6 were multiplied by 1.19 to convert them to 5-year return period (Debo and Reese, 1995; O'Loughlin and Robinson, 1987) to allow more meaningful comparison (Fig. 7).

The method of selecting a runoff coefficient from Building Industry Authority tables tends to overestimate the coefficient compared to the results obtained from the monitored events, assuming that the method of adjusting measured data for event frequency is acceptable. This is particularly so for the dense residential subcatchments. The measured runoff coefficients may be lower due to the particularly low-angle topography of the study areas (Table 1). However, the coefficient of determination between the two methods is high (r^2=0.92). This suggests that determining the runoff coefficient on the basis of land cover is appropriate, i.e. the subcatchment with the highest predicted runoff coefficient due to land cover characteristics also had the highest measured runoff coefficient.

An objective of this study was to investigate the suitability of calibrating hydrologic models such as the Rational Method on a regional basis. This study does not attempt to provide regional relationships for the runoff coefficient, due to the short-term data collection, limited number of study sites, and lack of data to validate the results. For regionalisation, areas for further work would include quantifying the role of event magnitude and assessing the methods for determining the time of concentration. For nearly all the study subcatchments, the runoff coefficient increased with event magnitude. This is consistent with the findings of other studies (Titmarsh *et al.* 1995; Pilgrim, 1982) and means that the nature of the events used in determining the runoff coefficient limits the applicability of the derived values. Nonetheless the runoff coefficient can be related to the percentage of impervious cover in a catchment with a high degree of explanation. In addition, changes in location do not significantly affect the runoff coefficient, as subcatchments of the Mazengarb and Papamoa with similar characteristics had statistically similar runoff coefficients. Therefore it seems that a regional relationships could be used to predict the runoff coefficient for catchments in the New Zealand coastal zone.

Soil Conservation Service (SCS) method

The Soil Conservation Service (SCS) loss model is widely used for estimating floods in small- to medium- sized ungauged catchments. Although developed in the United States it has been widely applied, for example, in Australia (Titmarsh *et al.*, 1995; Hoesein *et al.*, 1989), Canada (Madramootoo and Enright, 1988) and Asia (Muzik, 1993). Following limited testing it has been recommended for use in New Zealand (Beca Carter Hollings & Ferner Ltd, 1999a, b; Auckland Regional Council, 1999).

In the SCS loss model the rainfall-runoff relationship is represented by equation 4:

Equation 4 SCS relationship between rainfall and runoff

$$\frac{F}{S} = \frac{Q}{P - I_a}$$

where

F = retention

S = potential maximum retention

Q = direct runoff

P = precipitation

I_a = initial rainfall abstraction (i.e. includes interception, initial infiltration and detention storage on the soil surface)

This can be rearranged to:

$$Q = \frac{(P - I_a)^2}{P - I_a + S}$$

For small experimental watersheds a relationship between I_a and S has been developed (I_a = 0.2S), thus allowing the relationship between Q and P to be expressed by one parameter, the curve number. The relationship between the potential maximum retention and the curve number (CN) is:

$$S = 25.4\frac{1000}{CN - 10}$$

Thus as the curve number increases, the amount of runoff per unit rainfall increases. Tables are available to predict curve number as a function of land use, land cover, soil classification, hydrologic conditions and antecedent moisture conditions (Hoggan, 1997). While the SCS model was originally developed for agricultural areas, its use has expanded into urban areas (Hjelmfelt, 1991) and a number of studies have shown that urbanisation leads to an increase in the curve number (Beca Carter Hollings & Ferner Ltd, 1999a, b; Tsihrintzis and Hamid, 1997).

Prior to deriving values for the curve number for each of the subcatchments the I_a = 0.2S assumption was tested, because this equation has been found to over-predict I_a in New Zealand conditions (Beca Carter Hollings & Ferner Ltd, 1999b). Little is known about the derivation of the equation I_a = 0.2S except that considerable scatter was observed (Fennessey *et al.*, 2001). Initial abstraction is defined as the rainfall loss that occurs before surface runoff begins, and so it can be estimated directly from the hyetograph when the hydrograph is known (McCuen, 1998). Because high-resolution rainfall and runoff data were available, this was possible by determining the amount of rainfall not contributing to surface runoff (Table 6). One problem with this method is that the rainfall during the subcatchment lag is included in the estimate of initial abstraction; however, this was not considered important because the subcatchments were relatively small, and because the aim was to obtain only a rough estimate of initial abstraction.

Table 6 – Observed ranges of rainfall initial abstraction for each subcatchment

Subcatchment	Predominant land use	Initial abstraction (mm)
Mazengarb Catchment		
Realm Drive	Dense residential	0-1
Rosewood	Dense residential	0-0.8
Nikau	Rural	0.4-2.1
Ratanui	Low-density residential	0.2-3.3
Papamoa Catchment		
Evans Road	Dense residential	0-1.6
Pacific Cove	Rural	0-3.1
Beach Road	Dense residential	0.4-0.9

In all subcatchments the initial abstraction was often less than 1 mm; therefore, to use $I_a = 0.2S$ would significantly overestimate I_a. This can be demonstrated by calculating I_a from S: using the conventional tables gives a curve number=75 for a typical urban subcatchment (such as Evans Road), therefore S=84.7 and I_a = 17 mm. Thus events less than 17 mm should, theoretically, not produce surface runoff. This is not the case however (Fig. 8).

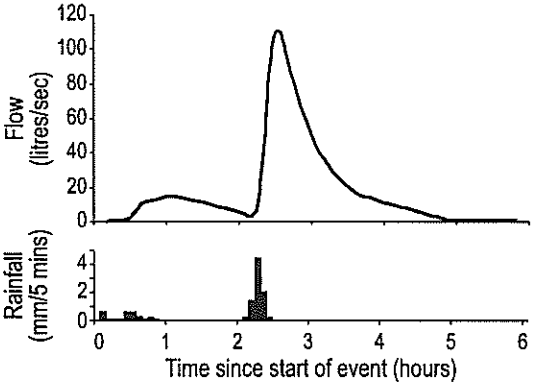

Figure 8 – Runoff response to 11 mm of rainfall in the Evans Road subcatchment

Auckland Regional Council (1999) recommends using an I_a of 0 mm and 5 mm for urbanised and rural areas, respectively. The data collected in the Mazengarb and Papamoa catchments suggests these values are more realistic than assuming $I_a = 0.2S$, although the 5 mm value may still be too large for small rural catchments.

For each event (Table 3) the curve number for each subcatchment was determined from the measured rainfall depth, runoff depth and estimated event I_a (to reduce errors in determining curve number) (Fig. 9).

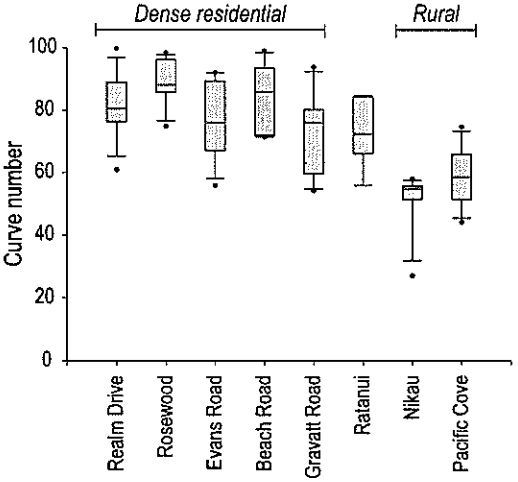

Figure 9 – Measured curve numbers for each subcatchment

Considerable variation in curve number within subcatchments was observed; again previous studies have suggested that event characteristics may account for this. The curve number tended to decline with increasing rainfall depth in the urban subcatchments and increase with increasing antecedent moisture conditions in the rural subcatchments, although the relationships were weak (Fig. 10).

These observations are consistent with previous studies (Tsihrintzis and Hamid, 1997; Titmarsh *et al.*, 1995; Hoesin *et al.*,

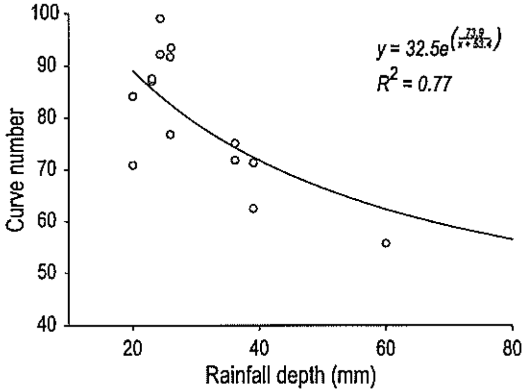

Figure 10 – Curve numbers as a function of rainfall depth, Papamoa subcatchments

1989; Wood and Blackburn, 1984). The effect of antecedent moisture conditions resulting in a higher curve number is more pronounced in rural areas because there is less impervious cover, hence greater potential for storage. The tendency of the curve number to decrease with increasing rainfall has been documented in other studies but not fully explained (Tsihrintzis and Hamid, 1997; Hoesein *et al.*, 1989). Even though rainfall depth is used in the calculation of the curve number, a secondary relationship between curve number and rainfall depth indicates that the equation may not account for all factors that influence the relationship between precipitation and runoff volume.

Despite the intra-subcatchment variation (Fig. 9) the two-sample Kolmogorov-Smirnov statistical analysis showed that:

1. in general the dense residential subcatchments had statistically greater curve numbers than the rural subcatchments,
2. in general the curve numbers from the dense residential subcatchments in both catchments were statistically similar, and
3. the curve numbers from the rural subcatchments in both catchments were statistically similar.

Therefore, land use and curve number were related: median curve numbers from the dense residential subcatchments were between 76 and 88, while the median curve numbers from the rural subcatchments were in the 50s (Table 7).

Table 7 – Median curve numbers for the subcatchments

Subcatchment	Predominant land use	Median curve number
Mazengarb Catchment		
Realm Drive	Dense residential	81
Rosewood	Dense residential	88
Nikau	Rural	55
Ratanui	Low-density residential	72
Papamoa Catchment		
Evans Road	Dense residential	76
Pacific Cove	Rural	59
Beach Road	Dense residential	86
Gravatt Road	Dense residential	76

These median values of curve number can be explained, with a high degree of confidence, by the percentage of impervious area (Fig. 11; r^2=0.70 p=0.02). As the permeable area decreases, infiltration declines; hence, catchment losses are reduced and the curve number increases.

In a similar manner to that employed for the runoff coefficient it was possible to compare the derived curve numbers (Table 7) with those from the United States Soil Conservation Service (1986) (Fig. 12).

There is a high degree of fit between the observed median curve number and the value calculated from the conventional tables (r^2=0.88; p=0.01). However, the observed curve numbers tended to be higher than the calculated curve number, and the deviation from the 1:1 line increases as curve number increases, probably because the observed curve numbers were derived from high

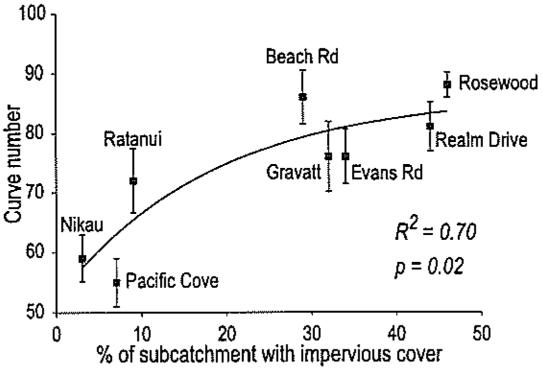

Figure 11 – Subcatchment median curve numbers as a function of the percentage of impervious cover

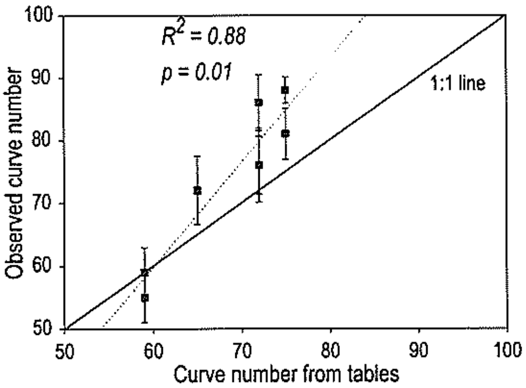

Figure 12 – Subcatchment median curve numbers compared to those from tables (United States Soil Conservation Service, 1986; McCuen, 1998).

frequency – low magnitude events. Thus if curve numbers are to be derived from observed rainfall – runoff data, the size and range of monitored events should be considered (Hawkins, 1998).

The derivation of a regionally calibrated method requires guidelines for selecting the parameter, and this is easiest if the parameter can be related to a physically-based quantity (Beca Carter Hollings & Ferner, 1999a). As in the findings for the runoff coefficient, because the curve number could be related to the percentage of impervious cover, using the percentage of impervious cover to estimate the effects of urbanisation on a regional basis appears viable. However, if regional relationships are being developed for rural catchments, factors such as soil type and vegetation cover should also be considered. Regional calibration of the curve number must also consider the variability in the curve number and the need for a large number of events for calibration, especially because curve number appears to decline with event magnitude (Fig. 10; Hawkins, 1998).

Conclusions

The objectives of this study were to determine the effect of urban development on the magnitude and timing of hydrologic response in the New Zealand coastal zone through direct measurement. This information was used to derive values of commonly used hydrologic model runoff parameters; and, to examine the potential for deriving regional relationships for estimating runoff parameters for New Zealand coastal zones. The underlying aim of this work was to provide experimental results for improved rainfall-runoff modelling in coastal zones currently undergoing rapid land use transformation.

The nature of the hydrologic response observed, and its change with urbanisation, is consistent with previous research. In the Mazengarb catchment the peak specific discharge for the dense residential subcatchments was approximately 900% greater than that for the rural subcatchment, while in the low-density residential subcatchment peak flow was only 150-200% greater. In the Papamoa catchment the difference in peak specific discharge between the dense residential subcatchments and the rural subcatchment was approximately 300%. The peak runoff in the dense subcatchments occurred much sooner than in the rural subcatchments and the recession rates were much quicker. Finally, the more urbanised subcatchments were much more responsive to changes in rainfall intensity than the rural areas, and had considerably less (or no) baseflow.

Within each subcatchment the derived runoff parameters varied between events. Some of this variation could be explained by event characteristics; however, the small number of events limited the conclusiveness of this analysis. Nonetheless some comments can be made. The runoff coefficient tended to increase with event magnitude, which is consistent with previous studies (Titmarsh *et al.*, 1995; Pilgrim, 1982) because, during less frequent storms, infiltration and other losses have proportionally less effect than in high-frequency storms; hence the runoff coefficient increases (Debo and Reece, 1995). In contrast, the curve number tended to decrease with event magnitude. This is appears to be an anomaly of the SCS method when deriving curve numbers for actual events (Hawkins, 1992).

Despite this intra-subcatchment variation, the nature of the hydrologic response and the relationship between land use and response could be quantified through the derivation of runoff parameters. The runoff coefficient (the ratio of peak flow to maximum rainfall intensity for the time of concentration), while varying within-subcatchments, was significantly greater for the dense residential subcatchments (median values 0.18-0.23) than the rural subcatchments (0.05-0.08). Similarly, the median SCS curve number tended to be higher for the dense residential subcatchments (76-88) compared to the rural subcatchments (50-60). However, the increase in the runoff coefficient is not as great as that anticipated in design standards (New Zealand Institute of Engineers, 1980; Davidson Ayson, 1996), and the measured runoff coefficient values were lower than those in design standards. This could be due to the low angle of the topography or because all the monitored events were of low magnitude and high frequency.

Crucially, especially for more widespread applicability of the results and the derivation of regional relationships, the most important control on the rainfall-runoff response was the percentage of impervious cover: it accounted for a significant amount of the observed variation in the runoff parameters. As the percentage of impervious cover increases, the amount of infiltration and storage decreases, resulting in more surface runoff, quicker surface runoff, and a higher specific peak flow. The nature of the observed results are consistent with the available literature but, more importantly, provide an initial empirical basis for standards, especially for New Zealand coastal catchments.

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