Auckland
Regional Council
TE RAUHITANGA TAIAO

Guidelines for stormwater runoff modelling in the Auckland Region

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CONTENTS

Glossary

Antecedent ground condition	Ground moisture condition preceding a storm event
Average recurrence interval (ARI)	Average period between exceedences of a given flow rate or rainfall
ARC	Auckland Regional Council
Areal reduction factor	Used to apply point rainfall estimates to large catchments
Channelisation factor	Used to reduce catchment response time to allow for higher velocities in engineered channels
Cover type	Landuse factor, eg: vegetation, bare soil, sealed pavement
Curve number	Defines the shape of the rainfall-runoff relationship and varies from 0 (no runoff) to 100 (complete runoff)
Dimensionless unit hydrograph	Hydrograph produced by a unit depth of rain excess falling uniformly in time and space over a unit area catchment
Heterogeneous catchment	Non-homogeneous catchment, eg: containing significant impervious areas draining by a separate piped network
Homogeneous catchment	A catchment where all areas drain through common flow paths
Hydrograph	Graph illustrating the variation of flow with time
Hydrological condition	Factor based on combination of parameters affecting catchment infiltration and runoff (vegetation density, surface roughness)
Hydrological soil group	Soil classification (A, B, C, or D) according to infiltration rate, where A is very high infiltration and D is very poor infiltration
Initial abstraction	Rainfall losses occurring before runoff begins (includes storage in depressions, interception by vegetation, evaporation, and infiltration)
Lumped catchment	A catchment modelled as a single surface collecting rainfall, draining directly through a single outlet
Potential soil storage	Maximum water storage capacity of a soil
Rainfall-runoff curves	A family of curves developed by the SCS relating cumulative runoff to cumulative rainfall
SCS	U.S. Department of Agriculture, Soil Conservation Service (now known as the Natural Resources Conservation Service)

Soil treatment	Factor describing management of agricultural lands (eg: tillage, terracing)
TR55	SCS Technical Release No. 55, “Urban Hydrology for Small Watersheds”, June 1986
Temporal rainfall pattern	Variation of rainfall intensity with time through a storm
Time of concentration	Time for a water particle to travel from the hydraulically most distant point of a catchment to the outlet

Definition of Symbols

A	km^2	Catchment area
C	-	Channelisation factor
c*	-	Dimensionless runoff index
CN	-	Runoff curve number
I	mm/hr	Rainfall intensity
I_{24}	mm/hr	24 hr average rainfall intensity
Ia	mm	Initial rainfall abstraction
k	-	Hydrograph number
L	km	Catchment length, measured along the main channel to the top of the catchment
P	mm	Rainfall depth
P_{24}	mm	24 hr rainfall depth
Q	mm	Runoff depth
q*	$m^3/s/km^2/mm$	Specific peak flow rate
q_p	m^3/s	Peak flow rate
S	mm	Potential soil storage
S_c	-	Catchment slope calculated by equal-area method
t_c	hrs	Catchment time of concentration
t_p	hrs	Unit hydrograph time to peak
V	m^3	Runoff volume

1. Introduction

These guidelines present a recommended method for the application of the U.S. Soil Conservation Service[1] rainfall-runoff model to catchments in the Auckland Region. They are based largely on Technical Release No. 55 (TR55) prepared by the U.S. Soil Conservation Service (SCS, 1986).

The Soil Conservation Service (SCS) model has been selected for stormwater management design in the Auckland Region on the basis of an evaluation against gauged catchments (BCHF, 1999a, 1999b, 1999c). Those reports provide the background to the selection, calibration and validation of the method. Streamflow data from the gauged catchments have been used to select input parameters for the model (soil classifications, times of concentration, etc.) and to validate the model.

The model is recommended for use in stormwater management design in the Auckland Region. It has been designed as a standard tool that will provide consistent results from different users. It is suitable for:

- assessing the effects of landuse change,
- modelling both frequent and extreme events,
- applying to distributed (a network of sub-catchments) or lumped catchments
- and simulating natural systems as well as engineered systems (such as pipe networks).

The model can be applied using a number of available software packages to predict runoff volumes, flow rates, and the timing of peak flows. Peak flow rates can also be estimated using an alternative graphical method.

1.1 Model Overview

Key features of the stormwater runoff model are illustrated in Figure 1.1 and described below:

- Design 24 hour rainfall depths are provided in the form of rainfall maps covering the Auckland Region.
- A standard 24 hour temporal rainfall pattern, having peak rainfall intensity at mid-duration. Shorter duration rainfall bursts with a range of durations from 10 minutes to 24 hours are nested within the 24 hour temporal pattern.
- Runoff depth is calculated using SCS rainfall-runoff curves, with curve numbers determined from the SCS guidelines according to classifications assigned to Auckland soil types.

[1] now known as the Natural Resources Conservation Service, part of the U.S. Department of Agriculture.

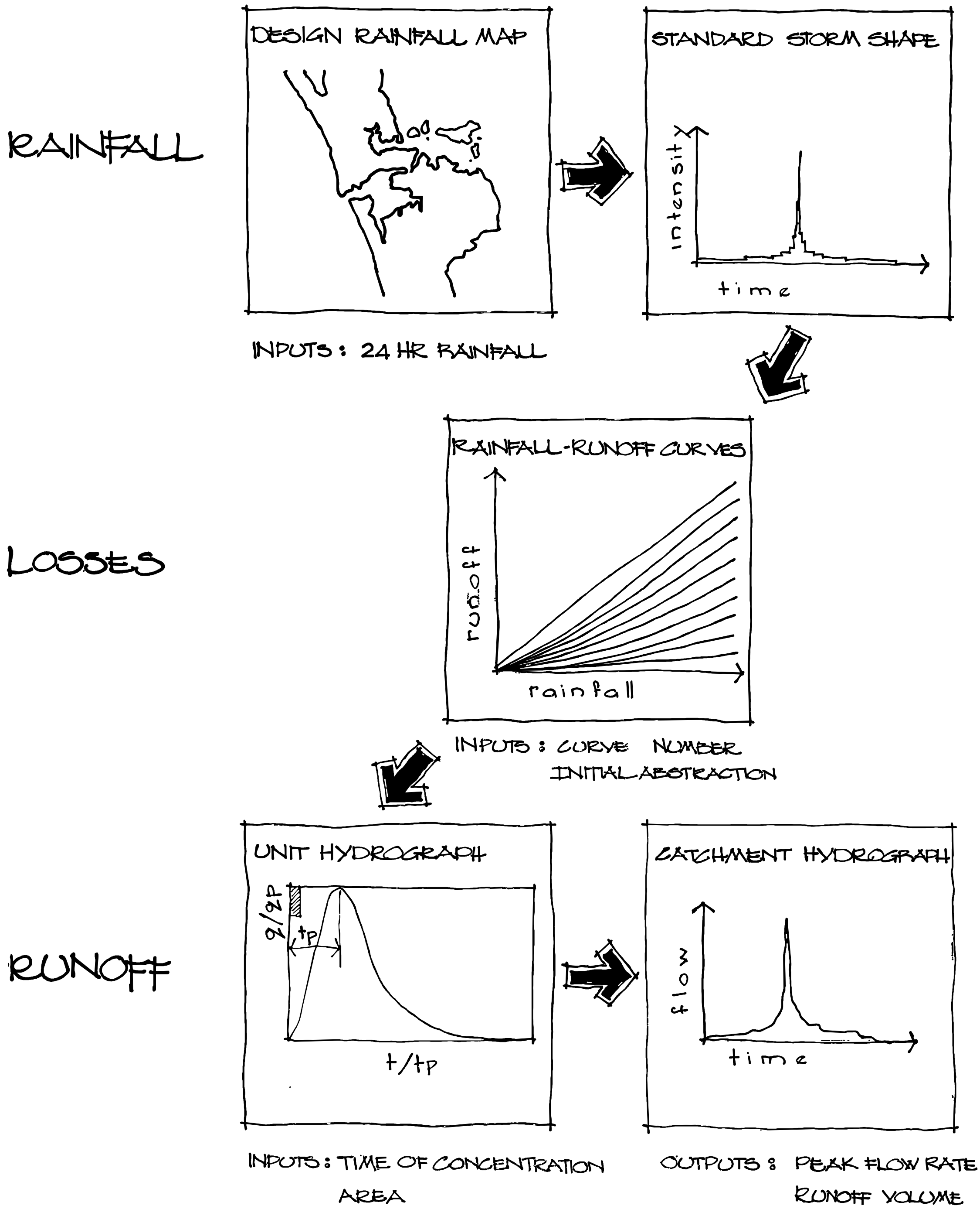


Figure 1.1 - Process diagram for the Stormwater Model

- Runoff hydrograph is calculated using the standard SCS synthetic unit hydrograph.

- Time of concentration is estimated using an empirical lag equation derived from a regression analysis of data from the Auckland Region.
- Separate analysis of pervious and impervious components of urban catchments.
- Effects of development on runoff depth are predicted using the standard SCS guidelines. Effects on catchment time response are allowed for using a channelisation factor and runoff parameter in the time of concentration relationship.

1.2 Limits of Application

- The model has been validated for relatively steep catchments in the Auckland Region, of up to 12 km^2 in size, with little hydraulic storage. For catchments with significant natural or engineered storage, separate hydraulic modelling of those areas will be necessary.
- The temporal rainfall pattern was derived statistically from rain gauge data representative of the Auckland Region and is appropriate for use within the Region.
- Rainfall loss and runoff timing parameters and have been validated for 'clayey' (weathered mudstone and sandstone) and 'volcanic' (granular loams, and loams underlain by fractured basalt) soil types. Other soil types should be modelled by interpolating the soil classification.
- The model is applicable to both rural and urban (or mixed) catchments. Model parameters have been validated for pasture, row crops and typical urban land cover. Parameters for other land cover types (eg: forest or scrub) have been provided based on the standard Soil Conservation Service (SCS, 1986) guidelines.
- The model has been prepared as a standard tool for converting a design rainfall depth into a design runoff event of the same exceedence frequency. Validation of the model against six gauged Auckland catchments gave a standard error of 21% for all average recurrence intervals (ARI). For ARI of 2 to 100 years, the model can be expected to be within ±25% at a confidence level of 90 percent. This level of accuracy is good for a regionally-calibrated model, for which average errors of 25% to 70% are typical (IEA, 1987).
- The model accuracy for historical flood events simulated from historical storms will be dependent on the antecedent ground conditions and spatial rainfall variation. Antecedent ground conditions are variable, depending on the season and the timing of the storm within the sequence of storms. If this type of information is required, it is recommended to re-calibrate the model runoff parameters (ie: curve numbers) from nearby gauged catchments for the particular storm and to estimate the spatial rainfall distribution from nearby rain gauges.

2. Rainfall

The design rainfall event is calculated from a standard 24 hour temporal pattern and an estimate of the design 24 hour rainfall depth.

2.1 Temporal Pattern

The temporal pattern of the 24 hour design storm is shown in Figure 2.1. It was derived from an analysis of depth-duration-frequency data from long-term rainfall records representative of the Auckland Region (BCHF, 1999c). Design rainfall bursts with a range of durations up to 24 hours were nested within a 24 hour storm, which was then normalised by the 24 hour rainfall depth.

The design storm indices, presented in terms of normalised rainfall intensity (I/I_{24}), are presented in Table 2.1.

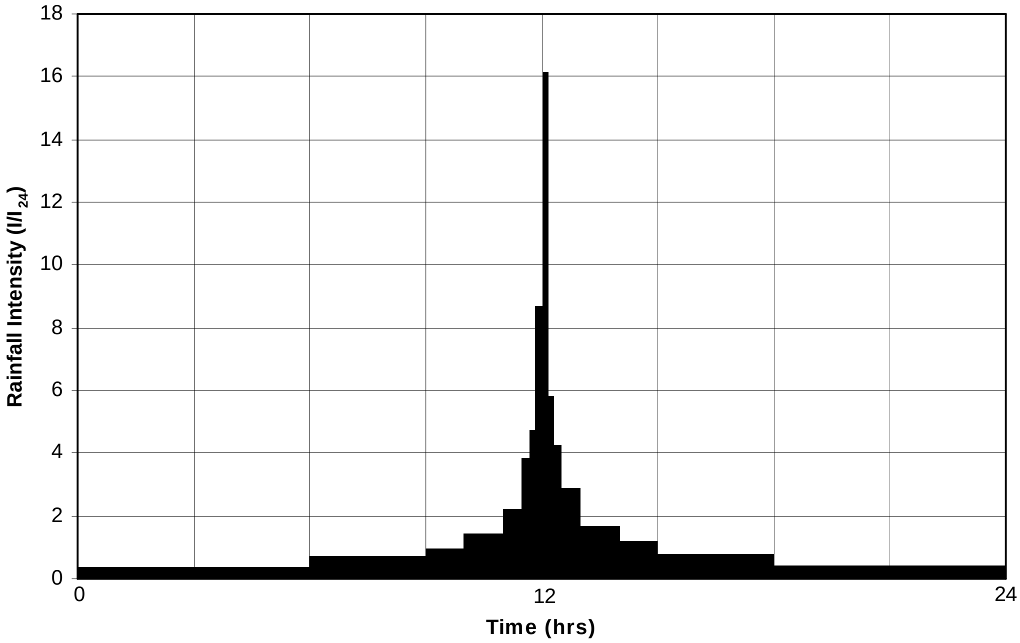


Figure 2.1 - Auckland Region 24 hour Design Storm

2.2 Design Rainfall Depth

The 24 hour rainfall depth should be obtained either from the design rainfall maps presented in Appendix A or from catchment-specific data if a suitable long term record is available. Contour maps of rainfall depth are presented for average recurrence intervals (ARI) of 2, 5, 10, 20, 50 and 100 years based on an analysis of rainfall gauge data across the region (BCHF, 1999c). Rainfall depths for other ARI within this range can be estimated by interpolating between maps.

Table 2.1 - Normalised 24 hour Design Storm		
Time (hrs:mins)	**Time Interval (min)**	**Normalised Rainfall Intensity (I/I_{24})**
0:00 -	360	0.34
6:00 -	180	0.74
9:00 -	60	0.96
10:00 -	60	1.4
11:00 -	30	2.2
11:30 -	10	3.8
11:40 -	10	4.8
11:50 -	10	8.7
12:00 -	10	16.2
12:10 -	10	5.9
12:20 -	10	4.2
12:30 -	30	2.9
13:00 -	60	1.7
14:00 -	60	1.2
15:00 -	180	0.75
18:00 - 24:00	360	0.40

2.3 Areal Reduction Factors

Areal reduction factors are used to apply point estimates of rainfall to large catchments. Areal reduction factors (ARF) should be used with the SCS method if it is applied to catchments larger than 10 km^2 in size. The use of the SCS method on large catchments has not been validated in this study and validation of model performance against field data will be necessary. In the first instance, it is recommended that the ARF presented in TP19 (ARC, 1992) be used. These were based largely on a study by Tomlinson (1980) and are shown in Table 2.2. For convenience, it is suggested that an ARF value is selected from Table 2.2 according to the catchment area and time of concentration and this factor is applied to the 24 hour rainfall depth input to the model.

Table 2.2 - Areal Reduction Factors for the Auckland Region (from ARC, 1992)							
Area (km^2)	Time of Concentration (hrs)						
	0.5	1	2	3	6	12	24
≤10	1.0	1.0	1.0	1.0	1.0	1.0	1.0
20	0.90	0.91	0.93	0.94	0.95	0.96	0.97
50	0.72	0.75	0.82	0.86	0.92	0.94	0.96
100	0.71	0.74	0.79	0.83	0.86	0.89	0.90
200	0.70	0.72	0.75	0.79	0.82	0.85	0.86
500	0.68	0.70	0.72	0.74	0.76	0.79	0.81

3. Rainfall Losses

3.1 Rainfall-Runoff Curves

The SCS rainfall-runoff curves are used to describe rainfall losses. A family of curves relating cumulative runoff to cumulative rainfall were derived by the SCS according to the following equation:

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S} \qquad (3.1)$$

where:

Q = runoff depth (mm)
P = rainfall depth (mm)
S = potential maximum retention after runoff begins (mm)
Ia = initial abstraction (mm)

The initial abstraction is defined as all losses occurring before runoff begins. It includes depression storage, interception by vegetation, evaporation, and infiltration. The SCS guidelines (SCS, 1986) suggested that initial abstraction be related to the soil storage parameter according to the empirical equation, Ia = 0.2 S. Data from Auckland catchments with a wide range of soil types indicate that constant initial abstraction depths are more appropriate. The following values have been derived from the calibration and should be used for pervious and impervious areas:

Table 3.1 - Initial abstraction depths

	Pervious areas	Impervious areas
Ia (mm)	5	0

The soil storage parameter is related to soil and landuse conditions of the catchment through the curve number, CN:

$$S = \left(\frac{1000}{CN} - 10\right)25.4 \qquad (mm) \qquad (3.2)$$

CN ranges from 0 for zero runoff, to 100 for total runoff. The family of rainfall-runoff curves is presented in Figure 3.1 for Ia = 0 and 5 mm.

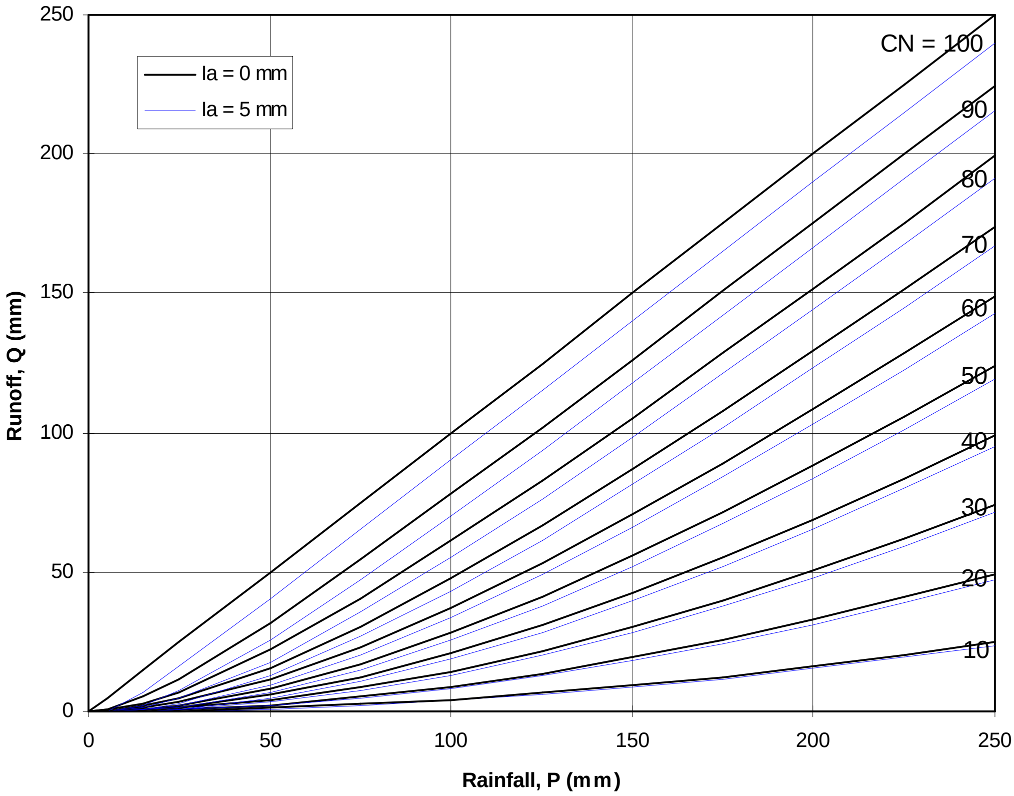


Figure 3.1 - Rainfall-runoff curves

3.2 Curve Numbers

The SCS guidelines (SCS, 1986) suggest that the major factors determining the curve number (CN) are the hydrological soil group, cover type, soil treatment, hydrological condition, and antecedent ground condition. Table 2-2 from the SCS guidelines presents curve numbers for urban and rural catchments with a range of these soil and landuse factors. Curve numbers for catchments in the Auckland Region should be selected using Table 2-2 (included in Appendix B) according to the guidelines presented below.

Runoff from catchments with a mix of soil or land use types can be modelled using an area-weighted curve number provided that the catchment is homogeneous. A homogeneous catchment is defined as a catchment where all areas drain through common flow paths. Where a catchment contains a significant impervious component connected to a piped network, the catchment should be considered heterogeneous. Heterogeneous catchments should be modelled by division into separate homogeneous sub-catchments, connected by hydraulic elements. The weighted curve number for a homogeneous catchment should be calculated as:

$$CN = \frac{\sum CN_i A_i}{A_{tot}} \tag{3.3}$$

Hydrological Soil Groups

The SCS hydrological soil groups are described as:

Group A soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels and have a high rate of water transmission (greater than 8 mm/hr).

Group B soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (4 to 8 mm/hr).

Group C soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (1 to 4 mm/hr).

Group D soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0 to 1 mm/hr).

On the basis of validation against gauged catchments in the Region, the following Hydrological Soil Groups should be used:

Table 3.2 - Hydrological Soil Classifications for prevalent Auckland Soils

Auckland Soil	**SCS Hydrological Soil Group**
Weathered mudstone and sandstone (Waitemata and Onerahi Series)	Group C
Alluvial sediments	Group B
Granular volcanic loam (ash, tuff, scoria)	Group A
Granular volcanic loam underlain by free-draining basalt	use CN = 17 for all pervious areas

Curve numbers for other soil types can be interpolated from the above classifications.

Land Use

Curve numbers should be selected based on soil type and land use based on SCS Table 2-2 (Appendix A). Land use type should be assessed by field reconnaissance, aerial photographs, or land use maps. Land use factors incorporated into the SCS guidelines are:

- cover type (type of vegetation or use),
- soil treatment (management of cultivated lands),
- hydrological condition (density of vegetation, surface roughness, etc.)

For example, Table 3.3 below presents curve numbers taken from SCS Table 2-2 for some typical Auckland conditions.

Table 3.3 - Curve numbers for typical Auckland conditions

Land use	**Group A Soil (volcanic granular loam)**	**Group B Soil (alluvial)**	**Group C Soil (mudstone/sandstone)**
Bush, humid-climate, not-grazed	30	55	70
Pasture, lightly grazed, good grass cover	39	61	74
Urban lawns	39	61	74
Crops, straight rows, minimal vegetative cover	72	81	88
Sealed roads, roofs	98	98	98

Impervious Areas

Impervious areas should be modelled with curve number of 98 and zero initial abstraction. Impervious areas within homogeneous catchments can be allowed for by using area-weighted values for CN and Ia. Impervious area should be measured from aerial photographs or by other methods (the percent impervious values in SCS Table 2-2a, Appendix B were not developed for Auckland conditions and should not be relied on). For homogeneous catchments:

$$CN = \frac{98A_{imperv} + CN_{perv}A_{perv}}{A_{tot}} \tag{3.4}$$

$$Ia = 5\left(\frac{A_{perv}}{A_{tot}}\right) \quad (mm) \tag{3.5}$$

Catchments containing significant impervious areas connected directly to a reticulated stormwater system should not be modelled as homogeneous. The impervious-connected component will have a more rapid response time than the pervious component of the catchment. This effect will be more marked in an urbanised catchment with volcanic soils. In such cases, a more realistic representation of the catchment may be obtained by modelling the connected-impervious areas and pervious areas as separate sub-catchments. Time response for the respective sub-catchments will be different and should be calculated according to the procedure in the following section. Any unconnected impervious areas (ie: those impervious areas draining onto pervious areas) should be included in the pervious sub-catchment.

4. Runoff

The runoff depth (calculated in Section 3) is converted to a catchment hydrograph using the dimensionless SCS unit hydrograph.

4.1 Unit Hydrograph

The SCS unit hydrograph was developed by averaging dimensionless unit hydrographs from a number of natural catchments with little or no storage (SCS, 1972). Individual hydrographs were made dimensionless by dividing by peak flow rate, q_p, and time to peak, t_p. The resulting dimensionless unit hydrograph is shown in Figure 4.1. The ordinates of this curve are presented in Table 4.1.

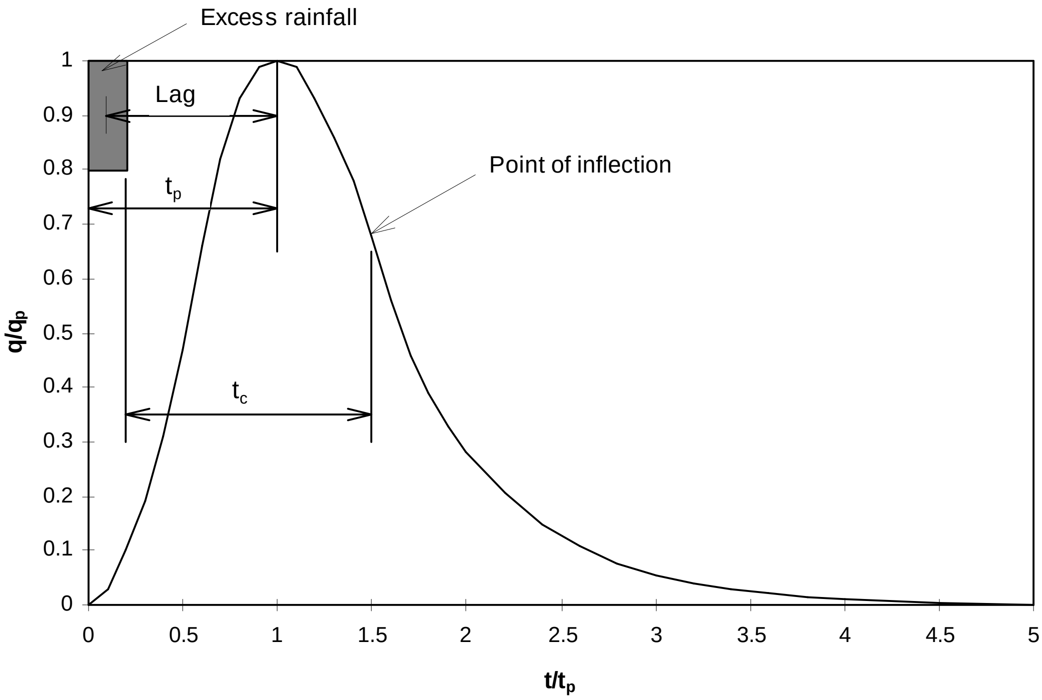


Figure 4.1 - SCS dimensionless unit hydrograph

The time to peak, t_p, of the SCS unit hydrograph is shorter than the catchment time of concentration, t_c. The SCS hydrograph is defined such that t_c is the time to the inflection point of the hydrograph recession limb. This leads to the following relationship (McCuen, 1998):

$$t_p = \tfrac{2}{3} t_c \tag{4.1}$$

Various software packages require the user to enter either t_c (eg: XP-SWMM32) or t_p (eg: HEC-HMS) in applying the SCS unit hydrograph.

Table 4.1 - SCS Unit Hydrograph ordinates					
t/t_p	**q/q_p**	**t/t_p**	**q/q_p**	**t/t_p**	**q/q_p**
0	0	1.1	0.99	2.4	0.147
0.1	0.03	1.2	0.93	2.6	0.107
0.2	0.10	1.3	0.86	2.8	0.077
0.3	0.19	1.4	0.78	3.0	0.055
0.4	0.31	1.5	0.68	3.2	0.040
0.5	0.47	1.6	0.56	3.4	0.029
0.6	0.66	1.7	0.46	3.6	0.021
0.7	0.82	1.8	0.39	3.8	0.015
0.8	0.93	1.9	0.33	4.0	0.011
0.9	0.99	2.0	0.28	4.5	0.005
1.0	1.00	2.2	0.207	5.0	0

The unit hydrograph is applied to a specific catchment by factoring it by the time to peak t_p, and the peak flow rate. The peak flow rate q_{ip}, from a short duration rainfall burst is related to the runoff depth of the burst Q_i, by:

$$q_{ip} = k\frac{Q_i A}{t_p} \tag{4.2}$$

The standard SCS unit hydrograph predicts $\frac{3}{8}$ of the runoff depth under the rising limb. This corresponds to a coefficient in the above equation of $k = 2(\frac{3}{8}) = \frac{3}{4}$ if consistent units are used. A hydrograph number of $\frac{3}{4}$ is recommended for the Auckland Region.

4.2 Time of Concentration

The catchment time of concentration should be calculated using the following equation, derived from a regression analysis of Auckland catchments (BCHF, 1999c):

$$t_c = 0.14\,C\,L^{0.66}\left(\frac{CN}{200-CN}\right)^{-0.55} S_c^{\,-0.30} \tag{4.3}$$

where: t_c = time of concentration (hrs)
C = a channelisation factor allowing for effects of urbanisation on runoff velocities (from Table 4.2)
L = the catchment length (km) measured along the main channel
CN = the weighted SCS curve number of the catchment
S_c = the catchment slope (m/m) calculated using the equal-area method

Equation 4.3 was derived using data from 18 rural catchments in the Auckland Region. Table 4.1 presents factors to be used with this equation allowing for the higher flow velocities in urban stormwater systems.

Table 4.2 - Channelisation factors	
Piped stormwater system	C = 0.6
Engineered grass channels	C = 0.8

In applying Equation 4.3 a minimum value of 10 minutes (0.17 hrs) should be adopted.

Urban Catchments

The time of concentration equation presented above should be used for homogeneous catchments. Where an urban catchment is modelled as heterogeneous, times of concentration for the pervious and impervious components of the catchment should be calculated individually using Equation 4.3 with channelisation factors and values of CN appropriate to each component.

5. Worked Example

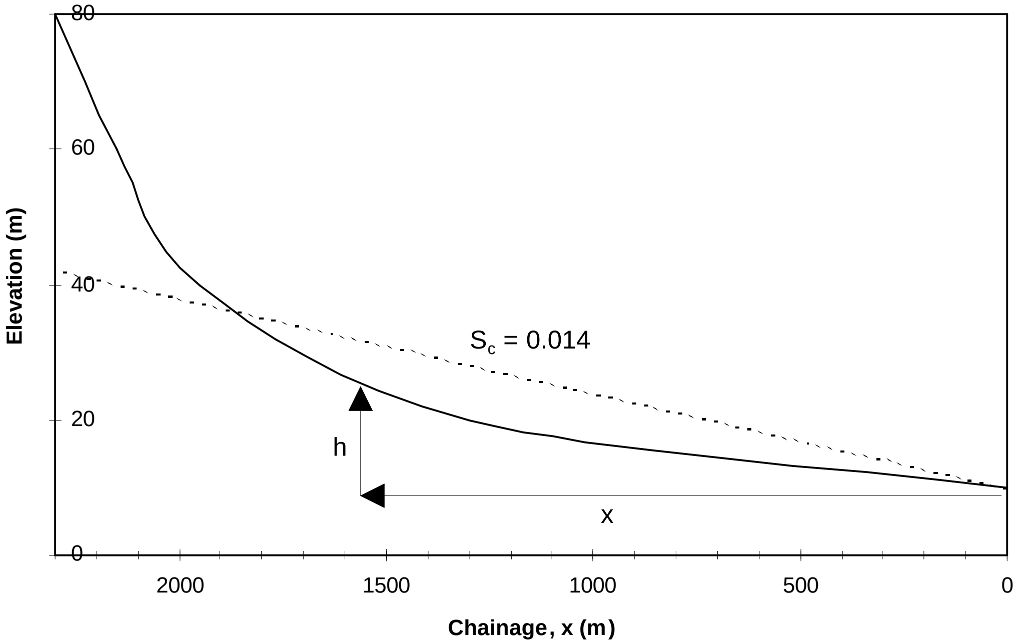
The use of the procedures given in the previous sections are illustrated by the following worked example. The objective is to compute runoff hydrographs from the existing urban Pakuranga catchment for the 2, 10, and 100 yr ARI events.

5.1 Catchment Details

Area = 312 ha

Length = 2.3 km (from point of interest to top of catchment)

Slope by equal area method:



elevation (m)	h (m)	x (m)	Δ x (m)	$\bar{h}$ (m)	Δ A (= $\bar{h} . \Delta$ x) (m^2)
10	0	0			
20	10	1300	1300	5	6500
40	30	1950	650	20	13000
60	50	2150	200	40	8000
80	70	2300	150	60	9000
			2300		36500

Slope, $S_c = \frac{2A}{L^2} = \frac{2(36500)}{2300^2} = 0.014$

5.2 Rainfall

Design 24 hour rainfall depths are selected for the catchment location from the contour maps in Appendix A.

2 yr ARI,	P_{24} = 75 mm (from Figure A1)
10 yr ARI,	P_{24} = 130 mm (from Figure A3)
100 yr ARI,	P_{24} = 200 mm (from Figure A6)

5.3 Rainfall Losses

Separating the catchment into pervious and impervious components and using Worksheet 1 (see pages 16-17) to calculate CN and Ia leads to:

a. ***Pervious component:***
(includes 166 ha pervious area and 20 ha unconnected impervious area)

Area	=	186 ha
CN	=	71.5
Ia	=	4.5 mm

b. ***Impervious component:***
(impervious areas connected to the piped network only)

Area	=	126 ha
CN	=	98
Ia	=	0 mm

5.4 Time of Concentration

Using equation 4.3 in Worksheet 1 with a channelisation factor of 0.6 to reflect the predominantly piped catchment gives times of concentration of 0.72 and 0.54 hours for the pervious and impervious catchment components respectively.