Chapter 6

The Empirical version of the Rational Method

The Empirical version is named because the parameters it uses (apart from rainfall data) are arbitrary and are generally based on experience or observation rather than field measurements obtained over a long period of time. This version has been used in Queensland for many years and remains the accepted method for small catchments with a high proportion of contour banked paddocks.

6.1 Description

While there are few long-term records of runoff from small agricultural catchments there are reliable, long-term rainfall records for most parts of Queensland. The Rational Method uses this data to predict peak discharge for design purposes. The assumption is made that a rainfall event of a particular Annual Recurrence Interval (ARI) and duration will produce a runoff event of the same ARI. In practice, a specific rainfall event will produce varying amounts of runoff depending on the conditions of the catchment at the time that the event occurs. If the design rainfall occurs on a dry catchment the resulting peak runoff will be lower than that for the design; and higher than the design runoff if it was a wet catchment. A design method must therefore be based on ‘average’ catchment conditions.

To gain an appreciation of the basis of this method, consider the runoff that would occur from the tin roof of a building as a result of a storm in which the rate of rainfall was constant (Figure 6.1). The resultant hydrograph from such a storm is shown in Figure 6.2.

Figure 6.1 Direction of runoff from a tin roof

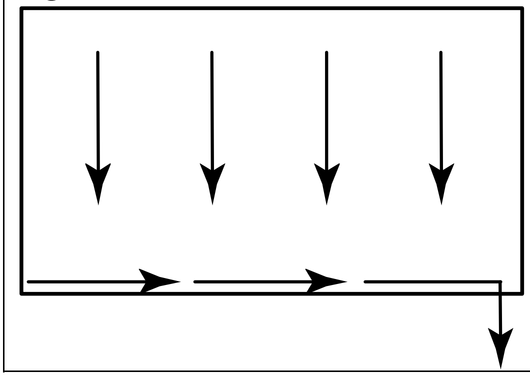
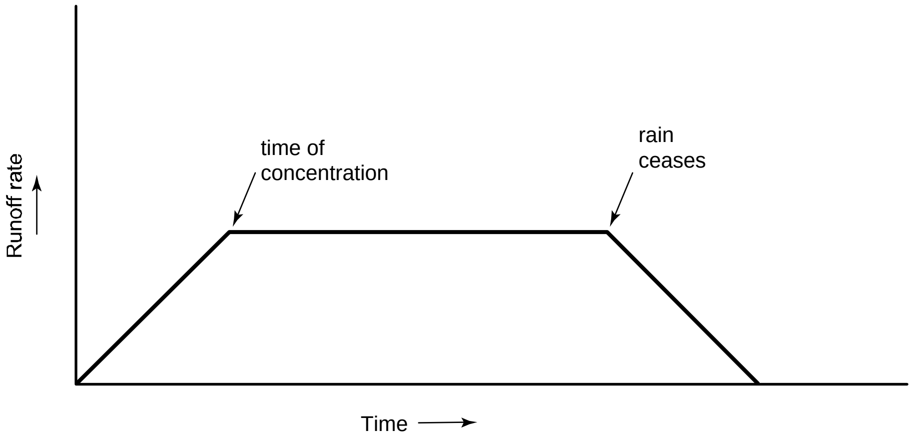


Figure 6.2 Resultant hydrograph from rainfall on a tin roof



After the commencement of rain, the rate of runoff would increase until it reached a peak. At this point the whole of the tin roof would be contributing to the outlet where the runoff was being measured. The period of time taken for the whole catchment to contribute is referred to as the *time of concentration* (tc). After this point has been reached, the constant rate of rainfall will ensure that the peak rate of runoff remains constant until such time as the rain ceases and the runoff rate will decline until no further runoff occurs.

To determine the peak rate of runoff for the tin roof, there are only two factors to consider:

- area of the roof
- rainfall intensity.

The formula used to determine the peak rate is:

$$\mathbf{Q = I\ A\ 0.00278}$$

Where

Q = peak discharge in m^3/s
I = rainfall intensity in mm/hr
A = area in hectares
0.00278 is to balance the units. A uniform rainfall rate of 1mm/hr on 1ha would produce a peak discharge of $0.00278 m^3/s$ if all of the rain resulted in runoff.

To use this formula for design purposes to predict rates of runoff from tin roofs, an appropriate rainfall intensity would need to be determined. In doing this, it would be necessary to consider the ARI of the event for which a design is required. Rainfall intensity–frequency–duration charts could then be used to determine a rainfall intensity for the appropriate time of concentration and ARI.

The formula, Q = I A 0.00278 could be applied to any ‘catchment’ if it is assumed that all of the rainfall resulted in runoff. While this is almost true for a tin roof it does not apply to a natural catchment.

To account for all of the variables that reduce the rate of runoff from a catchment, the Rational Method uses a single factor known as the runoff coefficient (C). The C factor is an estimate of the proportion of rainfall that becomes runoff. The C factor for a tin roof would be very close to 1. The factor for a soil similar to a beach sand would be as low as 0.1 or 0.2 because of the very high infiltration rates.

Taking into account the C factor, the Rational formula then becomes:

$$\mathbf{Q_y = 0.00278\ C_y\ I_{tc,y}\ A} \qquad \text{..........Equation 6.1}$$

Where

Q_y = design peak runoff rate (m^3/s), for an ARI of y years
C_y = the runoff coefficient for an ARI of y years, (dimensionless)
I_{tcy} = average rainfall intensity (mm/h), for the design ARI and for a duration equal to the ‘time of concentration’ tc, (minutes) of the catchment
A = catchment area (ha)
0.00278 is to balance the units. A uniform rainfall rate of 1mm/hr on 1ha would produce a peak discharge of $0.00278 m^3/s$ if all of the rain resulted in runoff.

If the area is in square kilometres (km^2) instead of hectares, the conversion factor is 0.278 (or 1/3.6).

It is accepted that the Rational Method is an oversimplification of a complex process. However it is considered to be suitable for runoff estimation for the relatively small catchments in which designs for soil conservation measures are carried out. As discussed in Chapter 4, *Designing for Risk*, the ability of a soil conservation structure to convey the runoff for which it was designed can vary by a factor of 5 (or greater) depending on the season and the stage of the cropping cycle when the event occurs. For this reason there is limited benefit in using a more complex model in an attempt to further refine the method of runoff prediction.

6.2 Runoff coefficient

The runoff coefficient (C_y) is defined as the ratio of the flood peak runoff rate of a given ARI to the mean rate of rainfall for a duration equal to the catchment 'time of concentration' and of the same ARI. The runoff coefficient attempts to take into account all catchment characteristics that affect runoff. Runoff coefficient values for use in soil conservation designs in Queensland are based on a number of factors including the potential of the land management system to produce runoff. It should be noted that these are arbitrary values and are not based on hydrological data.

Three 'runoff potential' categories are listed in Table 6.1.

Table 6.1 Runoff potential categories for use in designs for soil conservation purposes

Runoff potential	Forest	Pasture	Cultivation
1	Dense forest in undisturbed condition	Not applicable	Not applicable
2	Medium density forest with moderate levels of surface cover in most seasons	Pasture with high levels of pasture density in most seasons	Zero tillage / opportunity cropping. Rotations with crops or pastures with high cover levels
3	Forested area subject to high pressure with compacted soils and no surface cover	Pasture with low levels of pasture density in most seasons	Predominantly bare fallows with a rotation giving moderate to low levels of cover

Table 6.2 provides 10 yr ARI values for runoff coefficients based on the runoff potential categories from Table 6.1 as well as soil permeability values and topography. Soil permeability ratings can be obtained from district Land Management Field Manuals.

Table 6.2 Runoff coefficients for use with the Empirical version of the Rational Method

Runoff potential based on topography and land slope		10 yr ARI runoff coefficients		
		Soil permeability		
		High	Medium	Low
Runoff potential 1				
Flat	0–2%	0.1	0.2	0.3
Rolling	2–10%	0.1	0.3	0.4
Hilly	10–30%	0.2	0.4	0.5
Runoff potential 2				
Flat	0–2%	0.15	0.3	0.4
Rolling	2–10%	0.2	0.4	0.5
Hilly	10–30%	0.3	0.5	0.6
Runoff potential 3				
Flat	0–2%	0.2	0.4	0.5
Rolling	2–10%	0.3	0.5	0.6
Hilly	0–30%	0.4	0.6	0.7

To estimate runoff coefficient values for ARI's other than 10 years, the 10 Year ARI should be multiplied by the factors in Table 6.3. For example, the ARI 50 runoff coefficient can be obtained by multiplying the ARI 10 coefficient by 1.5. The values in Table 6.3 are based on values obtained for the Darling Downs Flood Frequency Version of the Rational Method (see Chapter 7).

Table 6.3 Conversion factors to determine peak discharge for different ARI's

ARI (years)	Conversion factor
1	0.5
2	0.6
5	0.8
10	1.0
20	1.2
50	1.5
100	1.8

There are two methods of accounting for situations where runoff coefficients vary within a catchment:

- Equivalent Impervious Area
- Proportionality.

6.21 Equivalent Impervious Area

The *Equivalent Impervious Area* of a catchment is the area that would produce a design flood of the same size as that estimated for the catchment if that Equivalent Impervious Area has a runoff coefficient of 1; this means that all the rainfall falling on the Equivalent Impervious Area runs off.

It is calculated by dividing a catchment into components having similar runoff producing characteristics. The Equivalent Impervious Area for each component is then determined by multiplying its area by its runoff coefficient. The Equivalent Impervious Areas for each component are then added to determine the Equivalent Impervious Area for the total catchment.

Equivalent Impervious Areas within the one ARI are additive. If the ARI is changed it is necessary to calculate a new Equivalent Impervious Area based on the runoff coefficient applicable to the new ARI.

As Equivalent Impervious Area incorporates both the runoff coefficient and the catchment area, the Rational Method formula then becomes:

$\mathbf{Q_y \;=\; 0.00278\ I_{tc,y}\ A_{ei,y}}$ ....Equation 6.2

Where

Q_y = design peak runoff rate (m^3/s), for an ARI of y years
$I_{tc,y}$ = average rainfall intensity (mm/h), for the design ARI and for a duration equal to the tc (minutes) of the catchment, and
$A_{ei,y}$ = Equivalent Impervious Area (ha) for the design ARI of y years

Example: Determine the Equivalent Impervious Area for a 90 ha catchment which consists of 20 ha of cultivation ($C_y = 0.6$), 30 ha of forest ($C_y = 0.3$) and 40 ha of pasture ($C_y = 0.4$).

Land use	Area (ha)	Runoff coefficient	Equivalent Impervious Area (ha)
Cultivation	20	0.6	12
Forest	30	0.3	9
Pasture	40	0.4	16
Total	**90**		**37**

6.22 Proportionality

The proportionality technique is used to provide a 'weighted' runoff coefficient for the catchment. For each component of the catchment having similar runoff producing characteristics, its assigned runoff coefficient value is multiplied by the ratio of its area to the total catchment area (Equation 6.3). These products are then summed to give a catchment proportional runoff coefficient.

$$\textbf{Component proportional } C_y = \frac{\textbf{component area x component } C_y}{\textbf{total catchment area}} \quad \text{................................Equation 6.3}$$

Example: Using the same data as in the previous example.

Land use	Area (ha)	Runoff coefficient	Proportional runoff coefficient
Cultivation	20	0.6	0.13
Forest	30	0.3	0.10
Pasture	40	0.4	0.18
Total	**90**		**0.41**

Note: The catchment proportional runoff coefficient multiplied by the catchment area equals the catchment Equivalent Impervious Area ie. 90 x 0.41 = 36.9.

6.3 Rainfall intensity

The average rainfall intensity for a design storm of duration equal to the calculated 'time of concentration' (tc) of a catchment is estimated using IFD (intensity, frequency, duration) information for the catchment.

The catchment 'time of concentration' is the time estimated for water to flow from the most hydraulically remote point of the catchment to the outlet. The Rational Method assumes that the highest peak rate of runoff from the catchment will be caused by a storm of duration just long enough for runoff from all parts of the catchment to contribute simultaneously to the design point.

The 'time of concentration' is calculated by summing the travel times of flow in the different hydraulic components. Those components may include overland flow, stream flow and/or flow in structures. Several flow paths may need to be assessed to determine the longest estimated travel time, which is then used to determine rainfall intensity.

The following guidelines should be used when estimating the time of concentration.

6.31 Contoured catchments

6.311 Overland flow

Overland flow travel times can be determined for the most remote part of the contour bay. The formula used for calculating overland flow is as follows:

$$\mathbf{t} = \frac{\mathbf{107\,n\ \sqrt[3]{L}}}{\mathbf{5\,\sqrt{s}}} \quad \text{..Equation 6.4}$$

Where

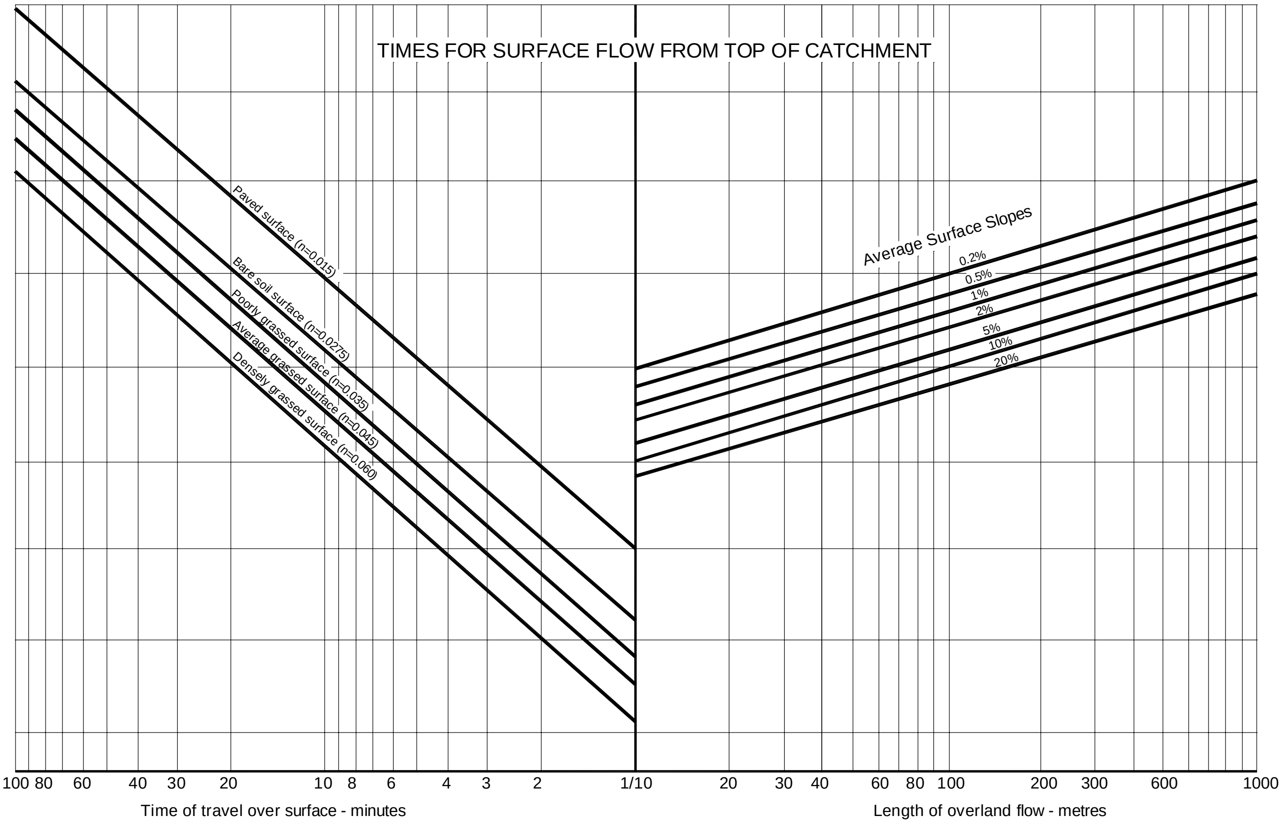
t = time of travel over the surface (minutes)
n = Hortons *n* values for the surface (Table 6.4)
L = length of flow (metres)
s = slope of surface (%)

Table 6.4 Hortons *n* values for different surface conditions

Surface condition	**Hortons *n* value**
Paved surface	0.015
Bare soil surface	0.0275
Poorly grassed surface	0.035
Average grassed surface	0.045
Densely grassed surface	0.060

The chart in Figure 6.3 is based on Equation 6.4. An average condition for the paddock surface should be chosen. Where stubble is normally retained on the soil surface, this would mean selecting for an average or poorly grassed surface. While Hortons *n* values are related to surface roughness, they should not be confused with the *n* values for roughness coefficients in the Manning equation (refer to Chapter 8, *Channel Design Principles*).

Figure 6.3 Travel time for overland flow



Formula $t = \frac{107\, n \sqrt[3]{L}}{5 \sqrt{s}}$

where
t = time of travel over surface in minutes
n = Horton's values for the surface
L = Lenght of flow in metres
s = slope of surface in %

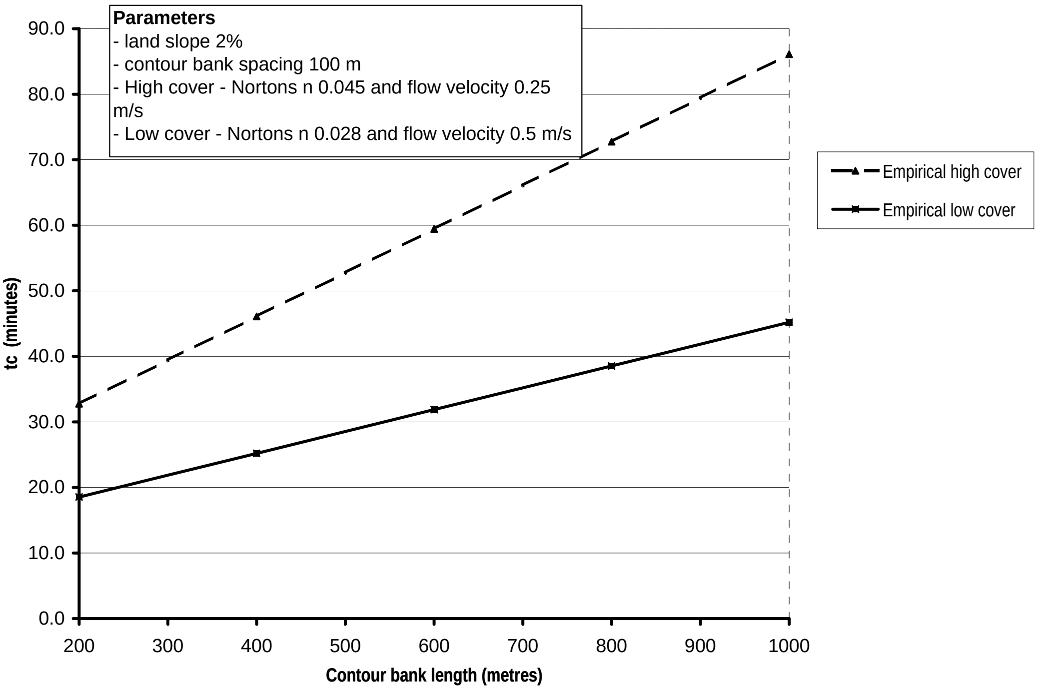
Example
Length of overland flow 200m
Average slope of surface 5%
Densely grassed surface (n= 0.060)
Time of travel = 27.2 minutes

6.312 Interception structure flow

Travel times along interception structures (contour and diversion banks) are calculated by dividing the length of flow by the design velocity of the structure. Since it is recommended that designs should be based on average conditions, it is appropriate to select a velocity appropriate to the average condition of the channel. In a paddock where there would normally be either a crop or standing stubble in a paddock, then a velocity representative of that situation should be chosen. Where contour bank channels have either a crop or standing stubble, it is most unlikely that the average velocity in the contour bank channel will exceed 0.25 m/sec even though the maximum acceptable velocity may be 0.5 or 0.6 m/sec. Chapter 9, *Contour banks* has more information on this topic.

Figure 6.4 shows a comparison of times of concentration in a contour bay comparing a high cover farming system with a low cover system.

Figure 6.4 Comparison of times of concentration in a contour bay for a high and low cover farming system



6.313 Waterway flow

Similarly for waterways, a velocity based on the average condition in the waterway should be chosen rather than the maximum design velocity for the waterway.

6.32 Non-contoured catchments

6.321 Overland flow

The overland flow chart in Figure 6.3 provides distances for flows of up to 1000 metres. A guide to estimating the length of overland flow is to assume that flow would begin to concentrate at a distance appropriate to the recommended contour bank spacing for that slope (refer to Chapter 9, *Contour Banks*). This means that lengths of overland flow would rarely exceed 100 metres despite the fact that the chart provides values for up to 1000 metres.

6.322 Concentrated flow

A velocity of 1 m/s is considered to be an acceptable value to use until a well-defined drainage line is reached.

6.323 Stream flow

Travel time for stream flow would not normally be required for the estimation of runoff from cropping lands. However it may need to be considered when preparing a design for the construction of diversion banks and gully control structures.

Travel time for stream flow is calculated by dividing the length of the stream by an estimated average velocity of the flow. Chow (1959) describes a method of determining a Manning roughness coefficient for a stream reach. This requires a summation of values given to factors affecting the roughness coefficient. The Appendix provides a guide to velocities that can be expected for a range of situations and was developed using Chow’s method.

6.4 Applying the empirical method

The following procedure is used when determining the design peak discharge at a design point. The Waterway design proforma (Figure 6.6) is recommended when using the procedure and for providing a record of the calculations. The computer program RAMWADE (**Ra**tional **M**ethod **Wa**terway **De**sign) takes users through the same steps as provided in the proforma.

1. Decide on the design ARI.
2. Allocate locations on the plan for design points (refer to Chapter 2, *Soil Conservation Planning).*
3. Estimate the ‘time of concentration’ for the design point.
4. From the IFD diagram for the district, determine the design rainfall intensity relevant to the ‘time of concentration’ and the required ARI.
5. Identify and measure component areas within the catchment and assign a runoff coefficient to each.
6. Either a) calculate the Equivalent Impervious Area for the catchment or b) calculate the catchment proportional runoff coefficient.

Calculate the design peak discharge by substitution into Equations 6.1 or 6.2 as appropriate.

The procedure can be simplified by preparing a graph relating the catchment Equivalent Impervious Area and ‘time of concentration’ for a particular ARI and locality. This chart is often referred to as a constant discharge diagram. An example is given in Figure 6.5. Similar charts can be made for any district using the relevant IFD data to solve Equation 6.2 and plotting the results.

Figure 6.5 Relationship between Equivalent Impervious Area and ‘time of concentration’ for the Kingaroy district

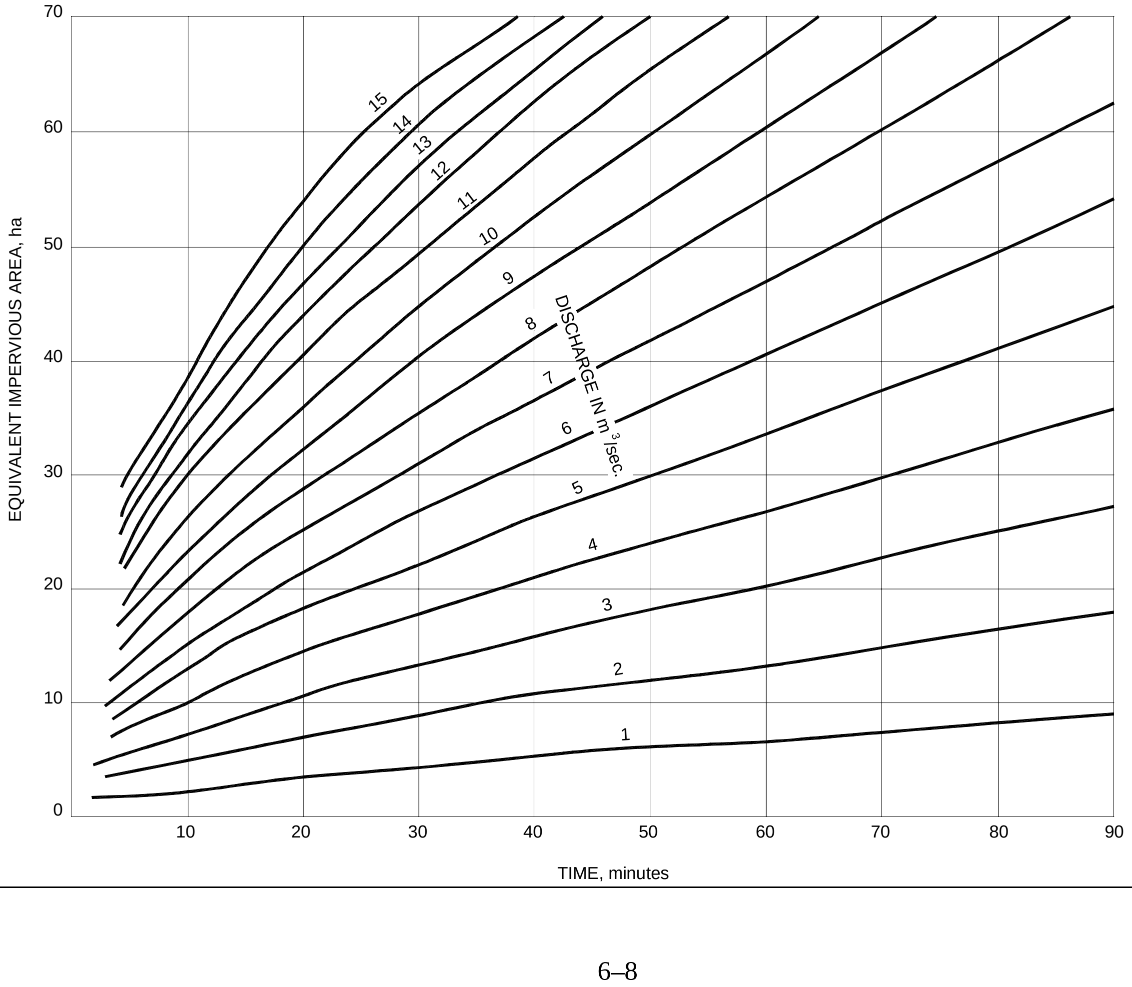


Figure 6.6 Waterway design proforma

Landholder			
Date	**Farm Code**	**Plan Number**	**Shire**
Contact details			
Property description			

1	Design Point							
2	Design ARI in years							
3	Length of overland flow (m)							
4	Average slope (%)	From survey or farm plan						
5	Time of travel for overland flow (min)							
6	Length of stream flow (m)							
7	Average slope of stream (%)							
8	Stream velocity (m/s)							
9	Time of travel in stream (minutes)	Row 6 / (Row 8 *60)						
10	Length of interception bank flow (m)							
11	Interception bank velocity (m/s)							
12	Time of travel in interception bank (min)	Row 10 / (Row 11 * 60)						
13	Tc previous design point (minutes)	Previous design point						
		Time						
14	Length of waterway flow (m)	Additional length if Row 13 is used						
15	Waterway velocity (m/s)	Estimated or previous design point						
16	Time of travel in waterway (minutes)	Row 14 / (Row 15 * 60)						
17	Time of concentration, tc, (minutes)	Total Rows 5,9,12, 13, 16 as applic						
18	**Rainfall Intensity, $I_{tc,y}$ (mm/h)**	**From IFD data for this location**						
19	Area at previous design point	Previous point						
		Total area						
		Equivalent Impervious Area (EIA)						
20	Area of pasture & average slope (ha)	Additional area if Row 19 is used						
21	Runoff co-efficient							
22	EIA, pasture (ha)	Row 20 x Row 21						
23	Area of cultivation & average slope (ha)	Additional area if Row 19 is used						
24	Runoff co-efficient							
25	EIA, cultivation (ha)	Row 23 x Row 24						
26	Other area & average slope (ha)	Additional area if Row 19 is used						
27	Runoff co-efficient							
28	EIA, other (ha)	Row 26 x Row 27						
29	Total area (ha)	Rows: 19+20+23+26						
30	**Total EIA, $A_{ei,y}$ (ha)**	**Rows: 19+22+25+28**						
31	**Peak discharge, Q_y (m^3/s)**	**Q_y = 0.00278 x I x $A_{ei,y}$**						
32	Design point slope (%)							
33	Retaining bank batters (1:Z (V:H))							
34	Minimum retardance value							
35	Design velocity, V (m/s)							
36	Bottom width, W (m)							
37	Maximum retardance value							
38	Flow depth, d (m)							
39	Settled bank height (m)	d + 0.15 m freeboard						

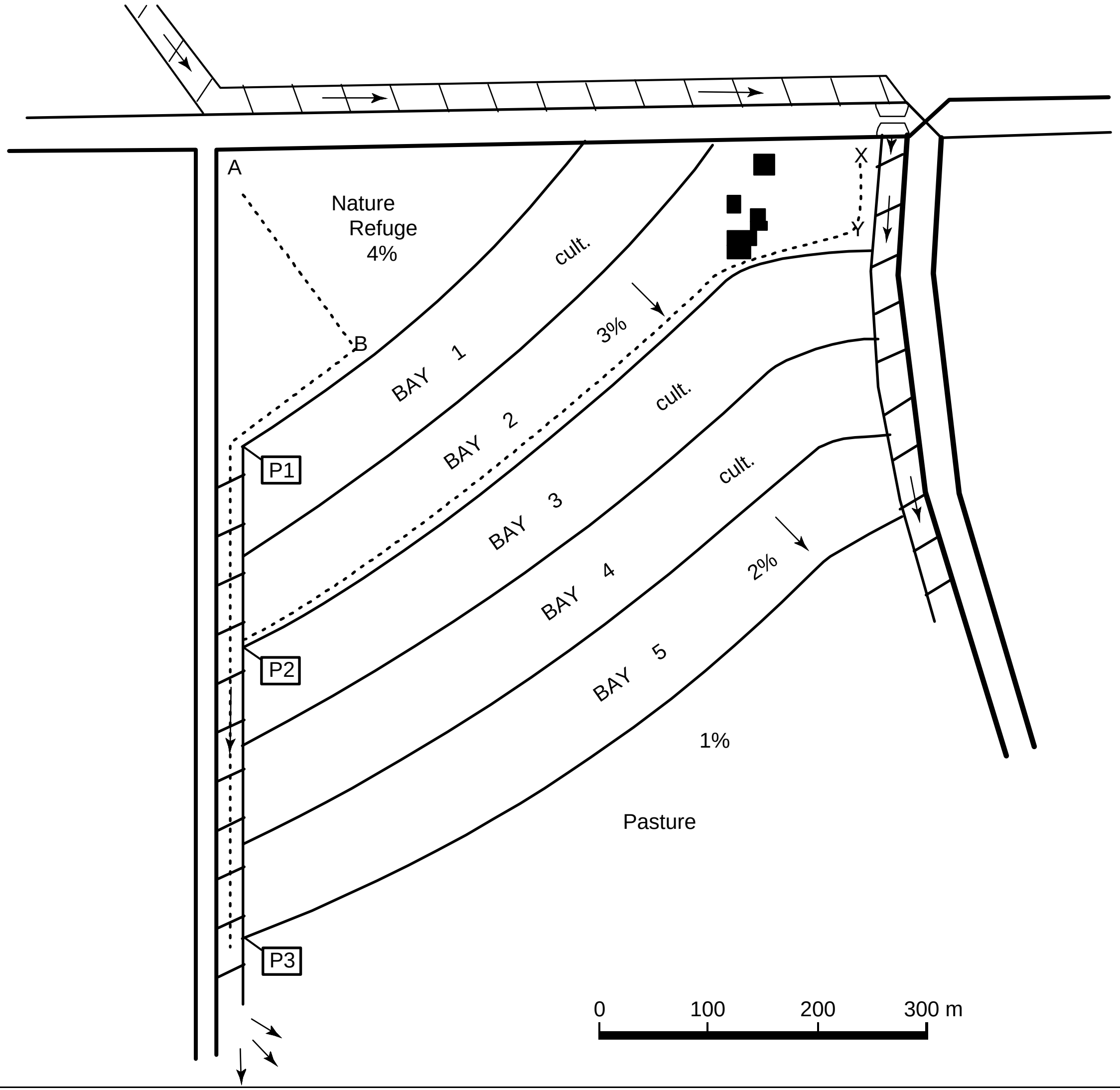
Comments

6.5 Example

Estimate the peak discharge for an ARI of 10 years for the waterway at design points, P1, P2 and P3 shown on the plan given in Figure 6.7. Assume the property is located in the Capella district, the soil is rated as being of low permeability and a farming system providing moderately low levels of cover is practiced. Use the waterway design proforma (Figure 6.6) and the information provided below:

Lengths		*Areas*	
A - B	290 m	Nature refuge	8 ha
B - P1	180 m	Contour bays 1+2	15 ha
X - Y	130 m	Contour bays 3+4+5	25 ha
P1 - P2	220 m		
P2 - P3	320 m		
Y - P2	820 m		
Design velocities		*Runoff coefficients (10 YR ARI)*	
Diversion bank	0.4 m/s	Nature refuge	0.4
Contour bank	0.3 m/s	Cultivation	0.6
Waterway	1.2 m/s		

Figure 6.7 Catchment for design example



Design point P1

Waterway design proforma row number	Design point P1	
3	Length of overland flow, A-B	290 m
4	Average slope, A-B	4%
5	Time of travel, overland flow, A-B *(Figure 6.3 assume average grassed surface)*	24 minutes
10	Length of diversion bank flow, B-P1	180 m
11	Design velocity, diversion bank	0.4 m/s
12	Time of travel, diversion bank (Row 10/(Row 11 x 60))	8 minutes
17	‘Time of concentration’ (Row 5 + Row 12)	32 minutes
18	Rainfall intensity, Capella (Figure 3.2)	88 mm/h
26	Area of nature refuge	8 ha
27	Runoff coefficient, nature reserve (Table 6.2 assume forest land use)	0.4
28	Equivalent Impervious Area (Row 26 x Row 27)	3.2
30	Total Equivalent Impervious Area	3.2
31	Peak discharge (0.00278 x Row 18 x Row 30)	0.8 m^3/s

Design Point P2

To determine the ‘tc’ for P2, it is necessary to compare the time of travel for flows along two different routes. Route A-B-P1-P2 should be compared with route X-Y-P2.

For route A-B-P1-P2, the travel time to P1 was calculated as 32 minutes (Row 17, previous chart). There is additional travel time along waterway P1-P2, 220 m at 1.2 m/s. This adds 3 minutes, giving a total time of travel of 35 minutes.

For route X-Y-P2, the time of travel is calculated below in the same order as previously for A-B-P1.

Waterway design proforma row number	Design point P2	
3	Length of overland flow, X-Y	130 m
4	Average slope, X-Y	3%
5	Time of travel, overland flow, X-Y. (Assume average grassed surface beside house and buildings, Figure 6.3)	20 minutes
10	Length of contour bank, Y-P2	820 m
11	Design velocity, contour bank	0.3 m/s
12	Time of travel, Y-P2 (Row 10/(Row 11 x 60))	46 minutes
17	Time of travel X-Y-P2 (Row 5 + Row 12)	66 minutes

Select the longest travel time to P2 (Here it is route X-Y-P2, being 66 minutes) and proceed.

Waterway design proforma row number	Design point P3	
17	‘Time of concentration’	66 minutes
18	Rainfall intensity, Capella (Figure 3.2)	58 mm/h
19	Total area, previous design point, P1	8 ha
	Total Equivalent Impervious Area, previous design point, P1	3.2 ha
23	Area of cultivation (contour bays 1 + 2)	15 ha
24	Runoff coefficient, cultivation (Table 6.2)	0.6
25	Equivalent Impervious Area, cultivation (Row 23 x Row 24)	9 ha
29	Total area contributing to P2 (Row 19 + Row 23)	23 ha
30	Total Equivalent Impervious Area for P2 (Row 19 + Row 25)	12.2 ha
31	Peak discharge (0.00278 x Row 18 x Row 30)	2.0 m^3/s

Design point P3

The longest route for determining ‘tc’ is X-Y-P2-P3.

Waterway design proforma row number	Design point P3	
13	‘Time of concentration’ for previous design point, P2	66 minutes
14	Length of waterway, P2-P3	320 m
15	Design velocity, waterway	1.2 m/s
16	Time of travel, P2-P3 (Row 14/(Row 15 x 60))	4 minutes
17	‘Time of concentration’, P3 (Row 13 + Row 16)	70 minutes
18	Rainfall intensity, Capella (Figure 3.2)	55 mm/h
19	Total area, previous design point, P2	23 ha
	Total Equivalent Impervious Area, previous design point, P2	12.2 ha
23	Area of cultivation (contour bays 3, 4, 5)	25 ha
24	Runoff coefficient, cultivation (Table 6.2)	0.6
25	Equivalent Impervious Area, cultivation (Row 23 x Row 24)	15 ha
29	Total area contributing to P3 (Row 19 + Row 23)	48 ha
30	Total Equivalent Impervious Area for P3 (Row 19 + Row 25)	27.2 ha
31	Peak discharge (0.00278 x Row 18 x Row 30)	4.2 m^3/s

■