Prediction of cover-dependent runoff amount and peak runoff rate for grazing land in Queensland

Final Report

Report prepared by

Bofu Yu
School of Engineering and Built Environment
Griffith University

for Queensland Water Modelling Network

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The Queensland Water Modelling Network (QWMN) is an initiative of the Queensland Government that aims to improve the state's capacity to model its surface water and groundwater resources and their quality. The QWMN is led by the Department of Environment and Science in partnership with the Department of Natural Resources, Mines and Energy and the Queensland Reconstruction Authority, with key links across industry, research and government.

This report is the work of the author and does not represent the views or policies of the Queensland Government.

Executive Summary

Runoff amount and the peak runoff are sensitive to the level of ground cover in grazing land. To use the Modified Universal Soil Loss Equation (or other models) for improved hillslope erosion prediction, methods are needed to estimate runoff amount and the peak runoff rate that vary in space in a consistent manner for application in the Great Barrier Reef catchments. For this study, it is assumed that data on or estimates of the peak rainfall intensities and runoff totals are available at the sub-catchment scale (50-100 km^2). Based on an extensive literature review and theoretical analysis, two alternative methods were developed to disaggregate the runoff total associated with the outlet of each sub-catchment into runoff amount for individual 30-m grid cells. The first method assumes an exponential decrease in the volumetric runoff coefficient as the ground cover increases, and the second assumes a linear decrease in the SCS Curve Number. In either case, the decrease in runoff is truncated at a threshold ground cover, beyond which the effect of cover on runoff is negligible. These two alternative methods for runoff disaggregation were described in detail and illustrated using the observed Nov/2000 runoff event for a sub-catchment (#399, Area = 178 km^2) in the Burnett-Mary basin. For prediction of the peak runoff rate, the scaling technique that requires rainfall and runoff amounts in addition to the peak rainfall intensity as input is recommended because this is the only method that has a real chance of being applied in a consistent manner throughout the Burnett-Mary basin and beyond. In addition to what has been published using rainfall-runoff data from Goomboorian in Southeast Queensland, Brigalow and Springvale catchments in Central Queensland, the scaling technique to predict the peak runoff rate was further evaluated with runoff data from 5 contour bays from the Greenmount site in Southern Queensland. The r^2 value for the scaling technique varied from 0.73 and 0.90 among the 5 contour bays, and the

overall Nash-Sutcliffe coefficient of efficiency for predicting the peak 6-min runoff rate was 0.825 when observed peak runoff rates were pooled together for all contour bays. The scaling parameter was found to be dependent on the catchment area as expected. This lends support for application of the scaling technique to ungauged sites elsewhere in Queensland.

Table of Contents

Contents

1. Introduction

Discharge of sediments, nutrients, and other pollutants from coastal catchments into the Great Barrier Reef (GBR) Lagoon has been a major area of concern because of their adverse impact on ecosystem health, and the reef health in particular. A customised representation of the eWater Source modelling framework, simply called Dynamic SedNet henceforth, is an integrated modelling tool for predicting streamflow, and sediment and nutrient loads in relation to variable climate, land use and management practices at the catchment scale. Dynamic SedNet has been implemented for 6 large regions along the Queensland coast. Dynamic SedNet considers hillslope, gully and streambank erosion processes and floodplain deposition, and predicts the rate of sediment generation and delivery to coastal waters. At present, the rate of hillslope erosion is predicted using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). Daily rainfall erosivity, known as EI_{30}, values were estimated from grid daily rainfall amount for all GBR catchments (Ellis and Searle, 2014; Yu, 1998). Rainfall erosivity is essentially the sole climatic driver for erosion predictions in the current implementation of Source for GBR catchments, i.e. there is no consideration of runoff-related variables in this prediction. This method has an issue that RUSLE calculates a soil loss amount whenever the rainfall amount exceeds a certain threshold while oftentimes no overland flow has occurred during the rain event to bring about sediment delivery.

In addition to rainfall, it is widely known that runoff is a critical factor in determining the rate of soil detachment and the rate of sediment transport. For instance, peak discharge was used to modify the USLE for erosion prediction as early as the 1970s (Onstad and Foster, 1975, Williams, 1975). For process-based erosion prediction technologies such as WEPP (Nearing et al., 1989) and GUEST (Misra and Rose, 1996; Yu and Rose, 1999), either the peak runoff rate or an effective runoff rate was used for predicting the rate of soil detachment and sediment transport on the hillslope. Freebairn et al. (1996, Table 9.8) found a large increase in the explained variance in soil loss when runoff amount and peak rate (i.e. either version of MUSLE) are used rather than just runoff alone. The need to predict runoff rates has been identified as an area for improvement in hillslope erosion prediction for GBR catchments within the Dynamic SedNet framework.

Given the need for predicting runoff amount and the peak runoff rate that is sensitive to cover variations in space and time, a project was supported through Queensland Water Modelling

Network and Department of Environment and Science to address the following research objectives:

- to develop methods, algorithms, and plug-ins for predicting runoff amount and the peak runoff rate that can be consistently applied throughout the GBR catchments
- to validate the methodology using data from field trials in Queensland
- to develop dataset for parameter values for implementation in all GBR catchments

The first report from the project presents the methodology for peak rainfall intensity prediction with potential applications in all GBR catchments. This second report focuses on runoff and peak runoff rate predictions, assuming that the peak rainfall intensity at a range of time scales is available everywhere in the GBR catchments. The report includes two separate parts. The first part (Chapter 2) includes a review of literature on the relationship between vegetation cover and runoff, especially for grazing land. This is followed by a detailed description of the theory and algorithm with a detailed numerical example for implementation for runoff prediction in the GBR catchments. The second part (Chapter 3) outlines the scaling technique for predicting the peak runoff rate and provides details on the technique based on an analysis rainfall and runoff data from Greenmount in Southern Queensland.

2. Runoff amount prediction

2.1 Literature Review

Vegetation cover, sometimes called ground cover, plays a critical role in surface runoff generation and soil loss (Quinton et al., 1997; Crockford et al., 2000; Liu et al., 2018). Vegetation cover consists of above-ground or canopy cover, and litter, and below ground cover. Collectively ground cover protects the soil from direct exposure to rainfall. More importantly, vegetation cover fundamentally changes water retention and infiltration characteristics. With reduction in cover, the interception storage capacity would decrease, and surface sealing is more likely to occur. The net result is that surface runoff would increase as the cover decreases. This literature review is focused on the cover-runoff relationship and how such a relationship is described mathematically, although the reduction in soil loss in general is even more pronounced than that in runoff, and the effect of cover on runoff and soil loss is often investigated together rather than separately.

An early study shows an exponential-like decrease in the runoff coefficient as a function of cover based on 8-year average values from grazing land in Rhodesia (now Zimbabwe) (Elwell and Stocking, 1976). Digitized Fig. 4 of that paper (Elwell and Stocking, 1976) showed that the rate of decrease in runoff coefficient is faster than an exponential function would allow (Fig. 2.1). Nonetheless, the exponential function can be used as a good approximation (see Table 2.1). Quinton et al. (1997) applied rainfall simulation to small plots (1.5 m^2) in south eastern Spain, and they showed that the relationship between cover and runoff coefficient is essentially linear on an event-basis. Chirino et al. (2006) showed an exponential decay in the runoff amount with cover for semi-arid area in Spain (Table 2.1). Morento-de las Heras et al. (2009) used an exponential function to describe the relationship between cover and runoff coefficient. On close inspection, the non-linear nature of the relationship is not pronounced, a linear relationship could have been used as in Quinton et al. (1997) (see Fig. 2.2). Garcia-Estringana et al. (2010) found a linear relationship between cover and the steady state runoff rate. Based on this compilation of investigations into the effect of cover on runoff, the following conclusions may be drawn: 1) runoff decreases as cover increases under all circumstances; 2) for individual events, whether measured in terms of runoff amount or runoff rate, the cover effect is approximately linear; 3) when aggregated, the relationship between cover and runoff coefficient is best described as an exponential decay function with the characteristic decay coefficient of 0.01 to 0.03 when cover is measured in percent (%).

Thus, around the world, the cover-runoff relationship is often described as an exponential delay function of cover in the form:

$$Q = Q_m e^{-\gamma c} \qquad (1.a)$$

or

$$R_c = R_{cm} e^{-\gamma c} \qquad (1.b)$$

where Q is the runoff amount as a function of cover, c, and Q_m is the runoff amount for bare ground ($c = 0$). Similarly, R_c the volumetric runoff coefficient (total runoff divided by total rainfall, and R_{cm} the runoff coefficient for bare ground ($c = 0$). The parameter γ represents the rate of decrease. The parameter γ is best interpreted as the percent reduction in runoff or runoff coefficient for one unit increase in vegetation cover because

$$\gamma = -\frac{dQ/Q}{dc} \sim \frac{-\Delta Q/Q}{\Delta c}$$

or

$$\gamma = -\frac{dR_c/R_c}{dc} \sim \frac{-\Delta R_c/R_c}{\Delta c}$$

In Australia, Greene et al. (1994) showed a linear relationship between cover and runoff rate for a grazing area in NSW. A rainfall simulator with a fixed intensity of 30 mm•h^{-1} was used for this research over a 1 m^2 area (Greene et al., 1994). Scanlan et al. (1996) carried out field studies in north Queensland near Charters Towers, and it was found that the runoff coefficient decreased with vegetation cover. An empirical relationship was fitted to predict runoff amount from vegetation cover, rainfall amount, the peak 15-min intensity, and soil water deficit. The proposed relationship between cover and runoff is non-linear (Scanlan et al., 1996). Owens et al. (2003) analysed runoff data from a number of plots in the Springvale catchment in Central Queensland, and advocated a linear reduction in the Curve Number (CN) as a function of cover to quantify the cover effect on storm runoff amount, and a similar linear relationship between cover and the Curve Number was adopted for PERFECT with supporting evidence from an Alfisol soil at ICRISAT Centre, Parancheru, India (Littleboy et al., 1996). The cover-CN relationship has been adopted in GRASP to quantify the cover effect on runoff to this day (Owens per. Comm.)

The equation to describe the relationship between cover and CN can be written as follows:

$$\mathrm{CN} = CN_m - \Delta c \quad where\ c < c_r \qquad (2.a)$$

and

$$\mathrm{CN} = CN_m - \Delta c_r \quad where\ c \geq c_r \qquad (2.b)$$

where *CNm* is the (maximum) curve number for bare ground ($c = 0$), and Δ is the reduction in CN unit for every 1% increase in cover, and c_r is a threshold cover level above which a constant CN value can be assumed.

Linear relationship between cover and the Curve Number and exponential relationship between cover and runoff coefficient are in fact quite similar. To provide empirical support for this, runoff data that were used to develop the linear relationship between ground cover and the Curve Number to quantify the effect of cover on runoff for the Springvale catchment (Owen et al. 2002) were re-analysed to test whether an exponential relationship between the cover and runoff coefficient could equally be used for the grazing catchment. Annual runoff data for 12 Springvale sub-catchments were analysed for the 7-year period (1988-1994). As shown in Fig. 2.3 below, the non-linear relationship between cover and runoff coefficient is quite evident. It can also be seen from Fig. 2.3 that the runoff coefficient is essentially independent of cover when cover exceeds 50-60%. Table 2.4 presents the rate of decrease, γ, as in

$$R_c = R_{co} e^{-\gamma c}$$

where R_c is the runoff coefficient, and R_{co} the bare ground runoff coefficient, and c cover in percent, for individual plots indicated here as troughs, and for the combined data set. For individual plots, the range in cover variations is usually limited (Fig. 2.3 and Table 2.4). As a result, it is difficult to fit a curve of exponential decay for the runoff coefficient as a function of ground cover for individual plots. When fitted with all data with cover ⩽ 55%, the following empirical relationship was obtained:

$$R_c = 0.57e^{-0.059c}, \quad R^2 = 0.54$$

The fitted curve is shown in Fig. 2.3 with cover up to 55%.

In summary, runoff decreases as vegetation cover increases, and runoff is less sensitive to cover where the level of cover is high. Thus, the effect of cover on runoff is inversely related to cover, and the rate of runoff decrease is reduced when the cover is relatively high.

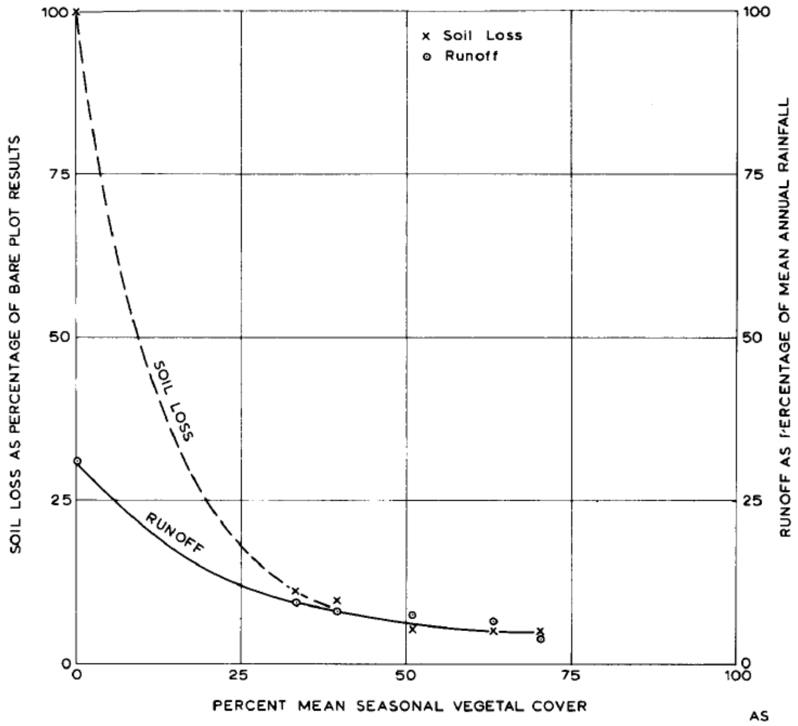

Fig.4. Mean annual soil loss and runoff variations with estimated mean percent vegetal cover on grazing land.

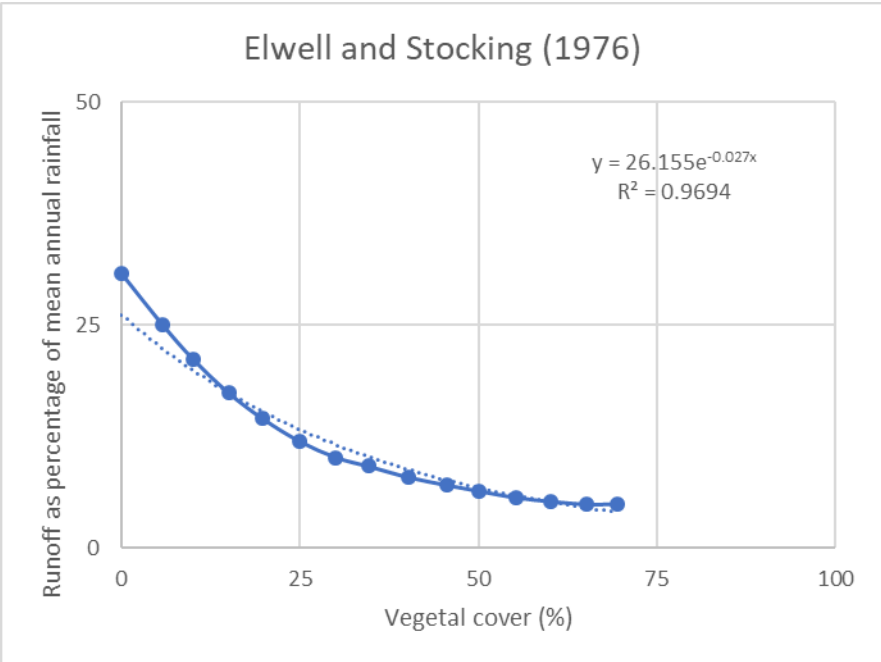

Fig. 2.1 The relationship between vegetation cover and runoff coefficient (Fig. 4 in Elwell and Stocking, 1976). The insert below the original figure shows the rate of decrease in runoff coefficient is higher than an exponential decrease.

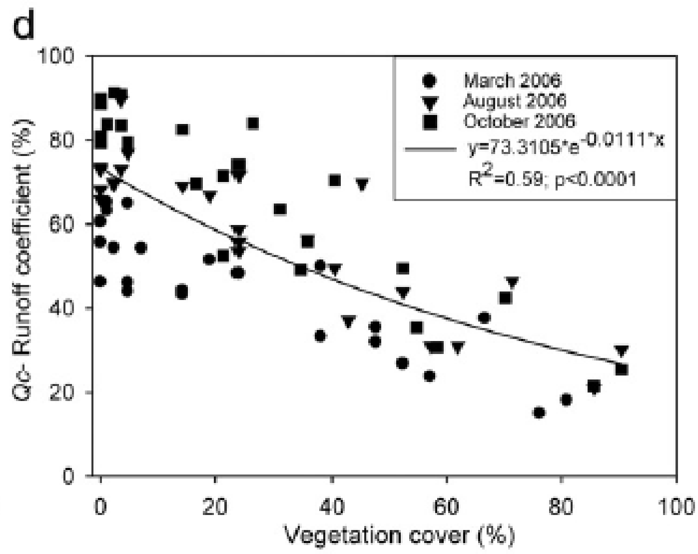

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Fig. 2.2 The relationship between vegetation cover and runoff coefficient (Fig. 4(d) in Morento-de las Heras et al., 2009) to show where a linear relationship could have been applied.

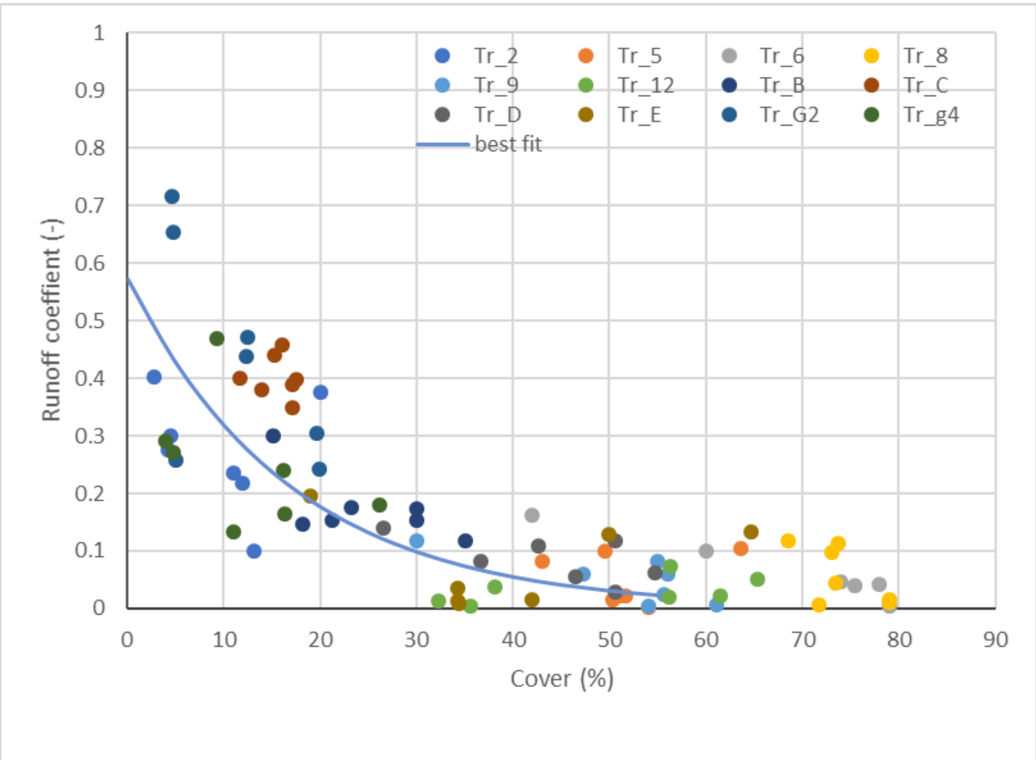

Fig. 2.3 The cover-runoff coefficient relationship for 12 sites labelled as troughs (Tr) in the Springvale catchment. The runoff coefficient was calculated as the ratio annual runoff over annual rainfall for each of the seven years (1988-1994).

Table 2.1 A compilation of the reported relationship between cover and runoff or runoff coefficient around the world.

Location	MAP (mm)	Size	Soil	Land use	Value for γ	Dependent variable	Method	References
Rhodesia	842	-	Sandy clay loam	Grazing	0.0272 (exp)	Runoff coefficient	Plot	Elwell and Stocking (1976)
Outback NSW	275 (median)	1 m^2	-	Grazing	0.15 (linear)	Runoff rate (mm/hr)	Rainfall simulator	Greene et al. (1994)
SE Spain	355	1-1.75 m2	-	Abandoned cropping land	0.004 (linear)	Runoff coefficient	Rainfall simulator	Quinton et al. (1997)
Alicante, SE Spain	292	2 x 8 m	Loam	Grass, shrub lands, forest	0.0233 (exp)	Runoff amount (mm)	Rainfall simulator	Chirino et al. (2006)
CE Spain	466	0.24 m^2	Clay loam	Reclaimed mine sites	0.0111 (exp)	Runoff coefficient	Rainfall simulator	Moreno-de las Heras et al. (2009)
Guadalajara, Central Spain	416	0.785m^2	Typic Rhodoxeralf	Abandoned cropping, pasture	0.891 (linear)	Runoff rate (mm/hr)	Rainfall simulator	Garcia-Estringana et al (2010)
Queretaro, Mexico	480	USLE plots	Vertisol	pasture	1.85-2.39 (linear)	Runoff (mm)	Rainfall simulator	Vasquez-Mendez et al. 2010

Table 2.2 Bare ground Curve Numbers (CN_m), Curve Number reduction per 1% increase in cover (Δ) and cover threshold.

Sites	CN_m	Δ	c_r (%)	References
Springvale, Qld	97	0.755(= 40/53)	53	Owens et al. (2003)
Northern Territory	91	0.625(=25/40)	70	Motha et al. (1995)
Patancheru, India	94	0.35 (=35/100)	100	Littleboy et al. (1996)

Table 2.3. Recommended parameter values for runoff prediction as a function of ground cover.

Parameters	*Rc* adjustment	*CN* adjustment
Cover threshold - c_r	50-60%	50-60%
Rate of decrease – γ (-)	0.01-0.03	n/a
Maximum Curve Number - *CNm*	n/a	90-97

Table 2.4 The rate of decrease in the runoff coefficient in relation to ground cover (γ) for individual troughs and the combined data set in the Springvale (Data source: ANNSUM5.xls, DATA-RALPH)

Trough	Area (m^2)	Cover range (%)	γ (-)	R^2
2†	14.2	2.8-20	0.018	0.06
5*†	50.2	43-63.6	Relationship break-down	
6†	37.8	42-79	0.069	0.57
8†	43.4	68.5-73.7	0.164	0.26
9		30-61.1	0.075	0.34
12†	62.1	32.3-65.4	Relationship break-down	
A*	30.2		No data available (?)	
B†	640.4	15.2-35	0.027	0.46
C†	73.9	11.7-17.5	0.005	0.12
D*†	340.0	24.5-54.7	0.035	0.33
E*	89.1	19-64.7	Relationship break-down	
G2*†	61.0	4.7-19.9	0.039	0.37
g4	?	4-26.2	0.026	0.23
All data		2.8-79	0.041	0.48
Data with cover ⩽ 55% only		2.8-55	0.059	0.54

* considered in Fentie et al. (2002)
† considered in Owens et al. (2003)

2.2 Theory and algorithm

Literature suggests that 1) runoff generally decreases as the vegetation cover increases; 2) the decrease is hardly noticeable once the cover exceeds some threshold. Thus, two alternative approaches are proposed to quantify the relationship between the vegetation cover and runoff amount. The first one is based on adjusting the runoff coefficient, and the second on the Curve Number.

Runoff coefficient adjustment

Given the decrease of the runoff coefficient as an exponential function of cover:

$$R_c = R_{cm}e^{-\gamma c} \quad where\ c < c_r$$

where Rc is the volumetric runoff coefficient, R_{cm} the maximum runoff coefficient for bare ground, c cover in %, and c_r the threshold cover (%) above which the effect of cover is assumed to be negligible, we have a constant runoff coefficient if the cover threshold is exceeded:

$$R_c = R_{cm}e^{-\gamma c_r} \quad where\ c \geq c_r$$

Thus, we have three parameters in total to fully define the relationship between cover and runoff, namely, c_r, γ and Rcm. If two of the three parameter values are known, the third one can be uniquely determined using the water balance principle. Suppose c_r and γ are known, and the total runoff volume (Vol) (ML) for a sub-catchment is given as

$$Vol = Q_t A$$

where Q_t is the average runoff depth (mm) and A the total area (km^2) for the sub-catchment. By definition,

$$Q(i) = R_c(i)P(i)$$

for individual rid cell, i. Regardless the adjustment scheme, the total volume of runoff must be conserved, i.e.

$$Vol = \sum_{c<c_r} P(i)R_{cm}e^{-\gamma c(i)}(\Delta a)_i + \sum_{c\geq c_r} P(i)R_{cm}e^{-\gamma c_r}(\Delta a)_i \qquad (3)$$

where $(\Delta a)_i$ represents the cell size (km^2) for cell i in the sub-catchment, and $P(i)$ is the rainfall amount for cell i. Combining eq. (1.a), (1.b) and (3) yields an estimator of the parameter R_{cm} for given c_r, and γ as follows:

$$R_{cm} = \frac{NQ_t}{\sum_{c<c_r} P(i)e^{-\gamma c(i)} + e^{-\gamma c_r} \sum_{c \geq c_r} P(i)} \qquad (4)$$

where N is the total number of cells and Q_t the average runoff depth for the sub-catchment defined above. In other words, if we know the rate of decrease in the runoff coefficient and threshold level of cover, the maximum runoff coefficient for bare ground can be uniquely determined to satisfy the water balance requirement.

Curve Number Adjustment

Unlike adjusting the runoff coefficient, there is no analytical solution to the water balance equation in terms of the unknown parameters, either CNm and Δ. A similar approach, however, can be adopted to formulate this as a root finding problem as outlined below:

Of the three parameters, c_r, CNm, Δ, suppose that c_r and CN_m are known. For given c_r, and CNm then, for each cell i, from 1 to N, compute the following

1) $CN(i) = CNm - \Delta c(i)$, note that for $c \geq c_r$, $CN(i) = CNm - \Delta c_r$,
2) The maximum retention storage (mm), $S(i)$,

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

3) Initial abstraction, Ia, in mm, as 20% of $S(i)$
4) Effective rainfall, $P_e(i) = P(i) - Ia(i)$, if $P(i) > Ia$; $P_e(i) = 0.0$, otherwise.
5) Storm runoff depth, $Q(i)$ in mm

$$Q(i) = \frac{P_e^2(i)}{P_e(i) + S(i)}$$

6) Solve the following nonlinear equation for Δ

$$f(\Delta) = NQ_t - \sum Q(i) = 0 \qquad (5)$$

In summary, to use either of the two adjustment schemes, i.e. adjusting the volumetric runoff coefficient, *Rc*, or adjusting the Curve Number as a function of cover, three parameters are required. Two of the three parameters can be estimated from literature (Table 2.1 and Table 2.2), and the third can be uniquely determined using the water balance principle. Recommended likely ranges for these parameters are presented in Table 2.3.

2.3 A numerical example

The method for runoff adjustment using each of the two schemes is illustrated below using streamflow data recorded at 136112A (Burnett River at Yarrol). The catchment area for the gauging station is 370 km^2, and the site has been in operation since 1/Oct/1965.

A runoff event occurred in the catchment over the period from 3/Nov/2000 to 7/Nov/2000. The total amount of rainfall recorded at the gauging station was 48 mm. Streamflow peaked on the 8^{th} of November with a mean discharge of 14.5 m^3/s for the day. The baseflow was estimated and removed from the observed flow to determine the surface runoff (Table 2.5). When summarised over the 5 days, the total surface runoff was 1674 ML, or a depth of 4.52 mm, indicating a surface runoff coefficient of 0.094 for the event.

Using P = 48 mm, Q = 4.52 mm, an overall value of S was 114.4 mm, and the associated CN value for the event was 68.9.

Table 2.5 Daily runoff data for the Nov/2000 event recorded at 136112A (Burnett River at Yarrol)

Date	Q($m^3 \cdot s^{-1}$)	Baseflow ($m \cdot s^{-1}$)	Surface runoff ($m \cdot s^{-1}$)
7/11/2000 0:00	0.153	-	-
8/11/2000 0:00	14.52	0.158	14.36
9/11/2000 0:00	3.35	0.163	3.19
10/11/2000 0:00	1.43	0.167	1.27
11/11/2000 0:00	0.62	0.172	0.45
12/11/2000 0:00	0.29	0.177	0.11

Sub-basin (#399) covers an area of 178 km^2 upstream from the gauging station. We used ground cover data at 30 m resolution for 1/Nov/2000 for this numerical example. In total, we had 198,151 cover observations for the sub-basin with a total area of 178 km^2. Cover varied from 0 to 93% among these 198,151 observations (Fig. 2.4). The total runoff volume from the area with cover data was assumed to be 805.6 ML (1674 x 178/370).

Rainfall amount varied from 32 mm to 69.7 mm for this event among the 198,151 cells (Fig. 2.5). For this numerical example, to apply the adjustment scheme for the volumetric runoff coefficient, the following parameter values were assumed:

$$\gamma = 0.03; \ c_r = 55\%$$

based on previous research (see Table 2.1 and 2.2). For this example, N = 198,151, and Q_t = 4.524 mm. Equation (4) was used to compute the runoff coefficient for bare ground, i.e. *CNm*. For this event, the average runoff coefficient was 0.0942, the maximum runoff coefficient was estimated to be 0.4381, and the minimum 0.0841. The relationship between cover and runoff coefficient is shown in Fig. 2.6 below for the event. It can be seen from Fig. 2.6 that the runoff coefficient is higher than the average runoff coefficient (0.0942) for areas of lower cover. Spatial distribution of runoff depth is shown in Fig. 2.7 using the method of runoff coefficient adjustment. The uniformly distributed runoff depth for the same event is shown in Fig. 2.8 for comparison.

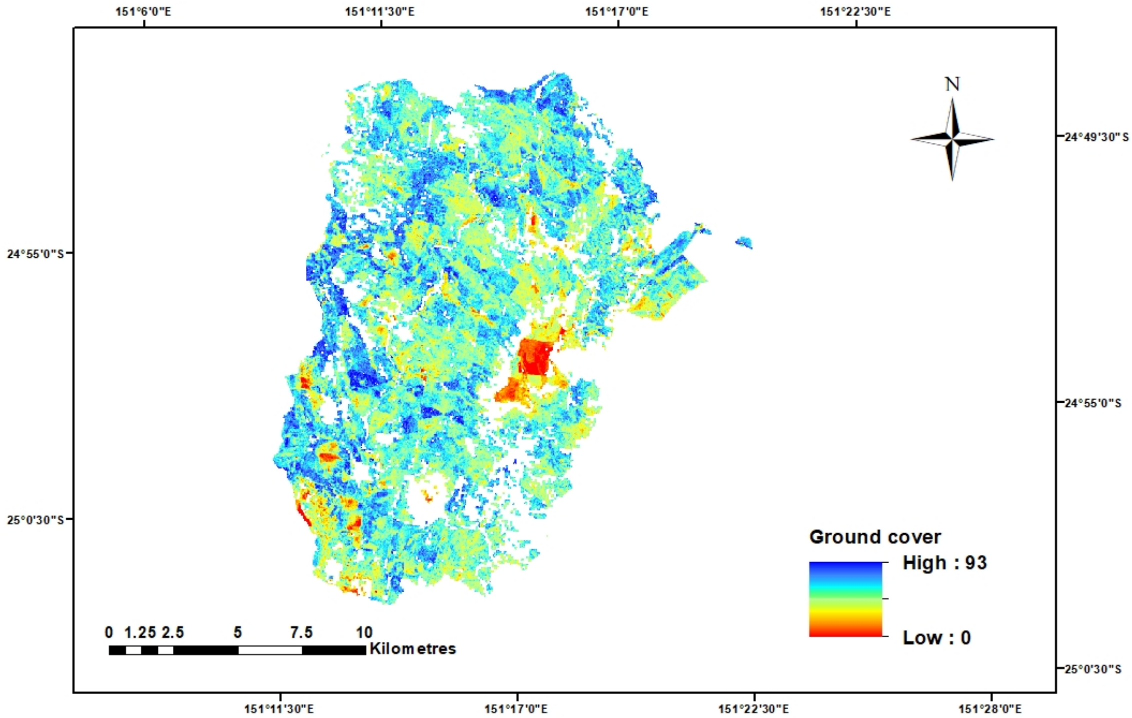

Fig. 2.4 Cover distribution on 1/Nov/2000 for the sub-basin #399 in the Burnett and Mary catchment.

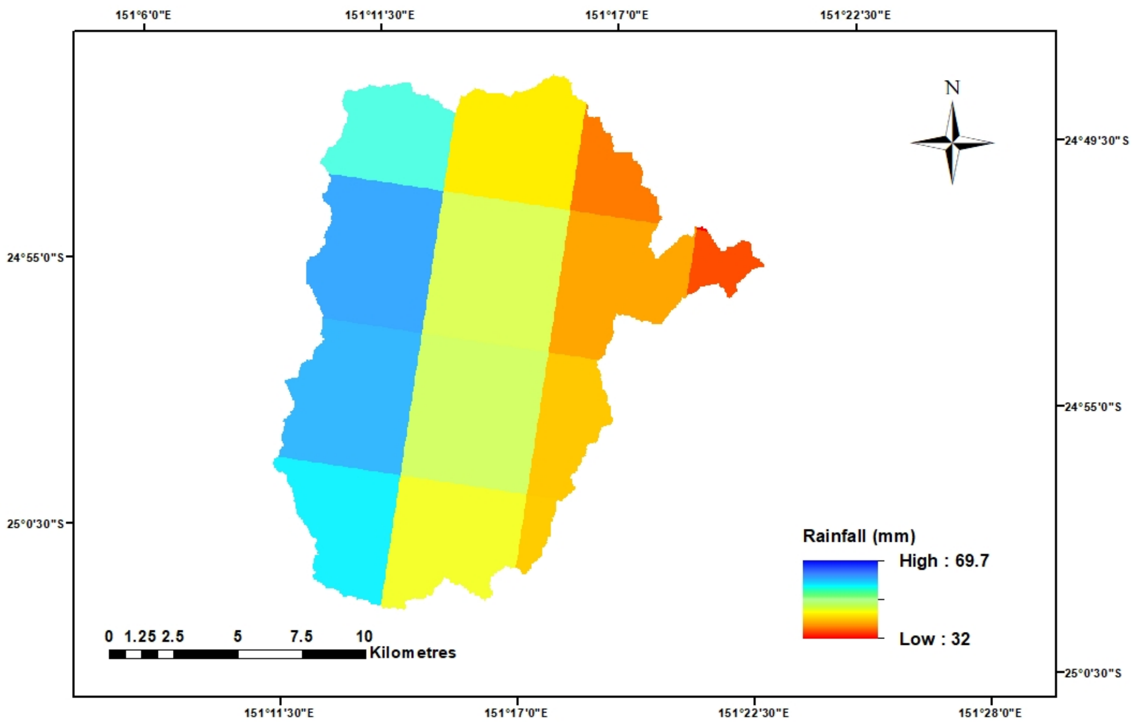

Fig. 2.5 Spatial distribution of event rainfall total (3/Nov/2000 to 7/Nov/2000) sourced from SILO.

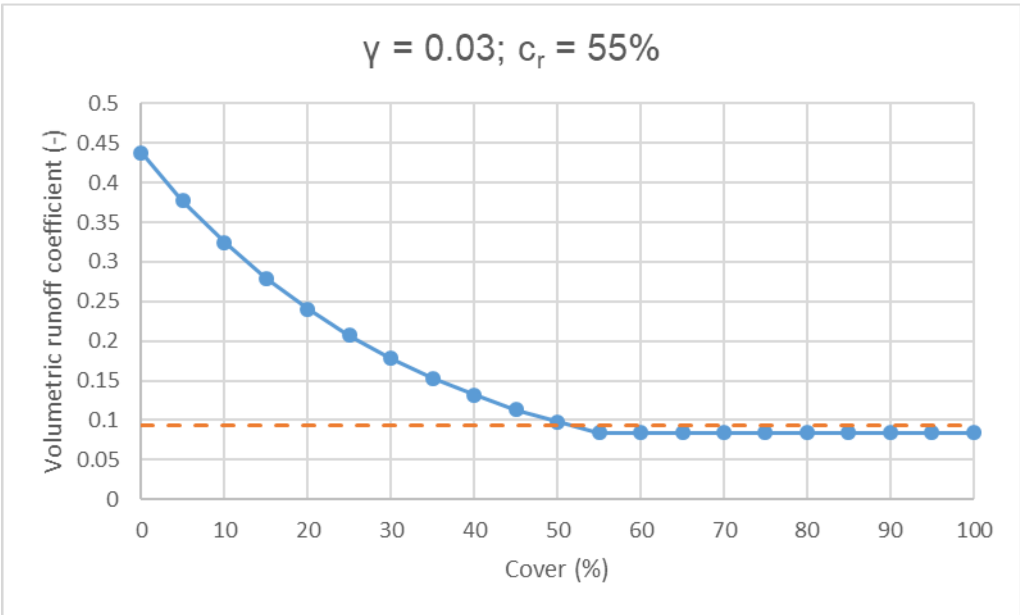

Fig. 2.6 The relationship between cover and runoff coefficient for the Nov/2000 event as an example. The dashed line represents the gross runoff coefficient for the event without taking into consideration the spatial variation in cover.

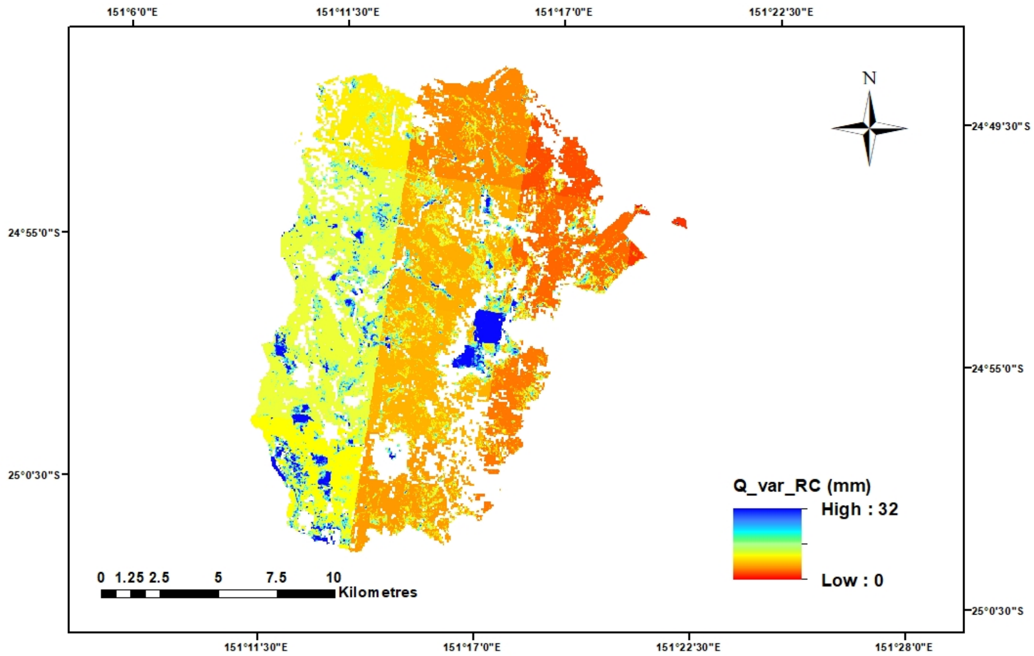

Fig. 2.7 Spatial distribution of runoff depth for the Nov/2000 event by adjusting the runoff coefficient as a function of ground cover.

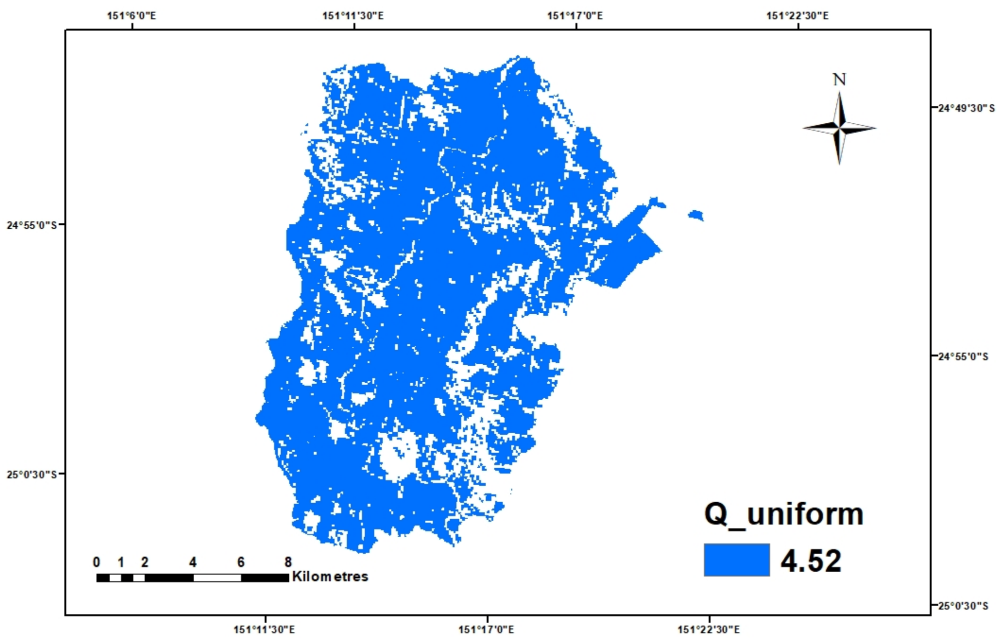

Fig. 2.8 Uniform runoff depth when variation rainfall and ground cover are ignored for the Nov/2000 event.

For the CN adjustment method, the following parameter values were adopted:

$$CN_m = 90; \; c_o = 55\%$$

For the Nov/2000 event, the solution to the nonlinear equation (Eq. 5) led to an estimate of the CN reduction per 1% increase in cover, Δ = 0.4184. The spatial distribution of runoff depth for the sub-catchment is shown in Fig. 2.9.

As rainfall varies in space, runoff coefficient is not a constant using the CN adjustment method. For comparison purpose, Fig. 2.10 shows the runoff coefficient as a function of cover assuming a uniform rainfall of 48 mm for the CN adjustment method. It can be seen from Fig. 2.10 that both methods represent a nonlinear decrease in runoff coefficient when cover is less than the assumed threshold cover of 55%. Once this threshold cover is reached, the runoff coefficient becomes constant. This constant coefficient may not be the same for these two methods because of the constraint imposed by water balance. The higher the runoff coefficient at lower ground cover, the lower the runoff coefficient where the ground cover is high.

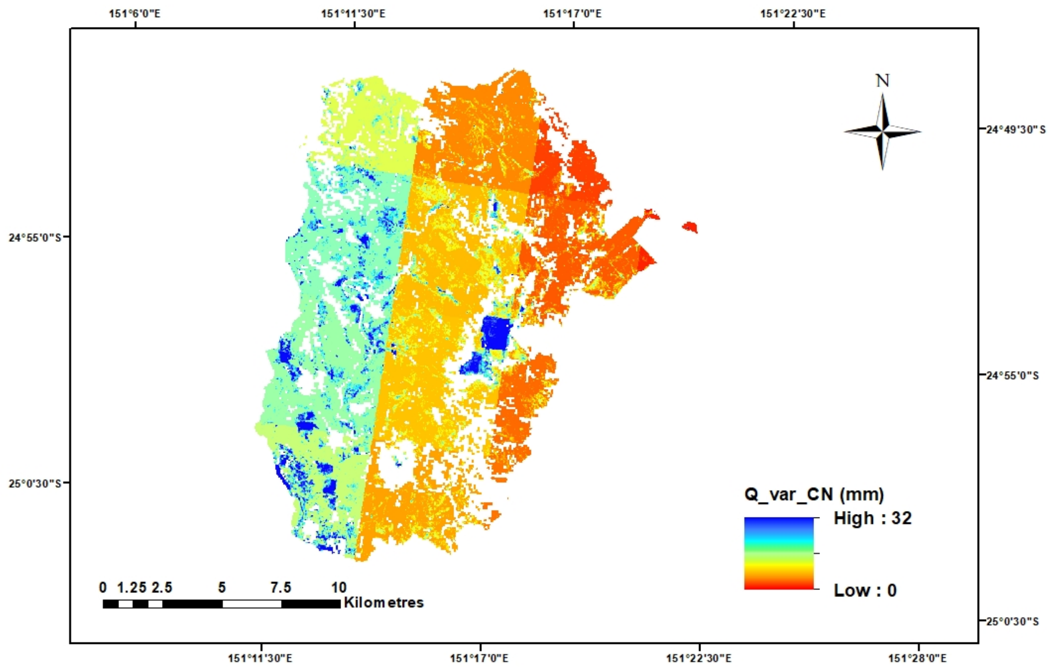

Fig.2.9 Spatial distribution of runoff depth for the Nov/2000 event by adjusting the Curve Number as a function of ground cover.

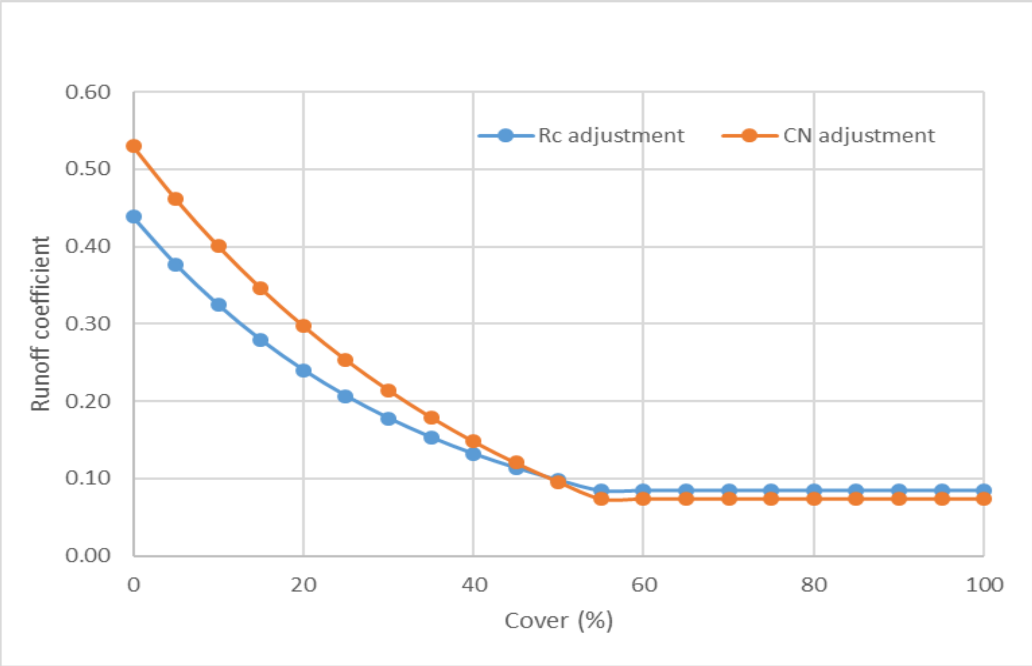

Fig. 2.10 A comparison of the two methods of quantifying the effect of cover on runoff amount in terms of the runoff coefficient with assumed rainfall amount of 45 mm and parameter values for the Nov/2000 event.

3 Prediction of the peak runoff rate

3.1 Introduction and literature review

For application of the Modified Universal Soil Loss Equation (MUSLE), the peak discharge, or the peak runoff rate, is needed in addition to runoff amount. For spatially distributed prediction of the peak runoff rate that is sensitive to variation in ground cover, the scaling technique was assessed and recommended for use for the GBR catchments. The scaling technique was first introduced in Australia to predict the peak runoff rate for erosion prediction using observed rainfall and runoff data for the Goomboorian site in Southeast Queensland (Yu et al., 1997). This was developed based on the principle of dimensional consistency, and this was supported empirically using field data for plots of 3 m wide and 36 m long on a 5% slope. The relationship between the effective runoff rate is strongly related to the peak intensity, runoff amount, and rainfall amount in the form:

$$Q_e = \alpha I_p \frac{Q_t}{P_t} \tag{3.1}$$

where Q_e is the effective runoff rate (mm/hr), I_p the peak rainfall intensity, and Q_t and P_t are runoff and rainfall totals, respectively. The r^2 varied between 0.72 to 0.96 for the 3 different surface treatments at the site and peak rainfall intensities at 4 different intervals (Yu et al. 1997). For 6-min rainfall data, the r^2 values varied between 0.83 to 0.96. Peak 6-min intensities were recommended because pluviograph data are more readily available at this temporal resolution in Australia.

Fentie et al. (2002) compared 8 different methods to predict hillslope runoff rates using data from the Springvale catchment in Central Australia. The plot area varied from 30.2 m^2 to 340 m^2. One of the 8 methods considered was the scaling technique. They show that the scaling technique with only 1 parameter is the second best method for Q_p prediction (r^2 = 0.84), and second only to the non-linear regression approach involving up to 5 parameters.

Unpublished results from the Brigalow Catchment Study also indicated the scaling technique could be used to predict the peak runoff rate for the forested, cropping and grazing catchments (area = 11.7-16.8ha) (Thornton and Yu, unpublished manuscript).

The scaling technique has the advantage of being dimensionally consistent, and less data demanding. For instance, Fentie et al. (2002) showed that the model performance could be marginally improved if the variable infiltration rate (VIR) model was used. This, however, would require detailed time series of rainfall intensity data for each grid cell for which peak runoff rate is to be predicted.

The scaling technique has been tested for runoff plots as well as small catchments, i.e. 108 m^2 at Goomboorian; 30.2-340 m^2 at Springvale, and 1.17-1.68 x 10^5 m^2 at Brigalow. For prediction of the peak runoff rate, it is most likely to apply the scaling technique at the 10^3 – 10^4 m^2 scale throughout the GBR catchments. The scaling technique was therefore further evaluated using rainfall-runoff data collected from contour bays at Greenmount in southern Queensland at ~10^4 m^2 scale.

3.2 Data and methods

Rainfall and runoff data were extracted from DES database in csv format for five catchments at Greenmount (south of Toowoomba) (Freebairn and Wockner, 1986). Runoff was measured and recorded at individual gauging stations using a V-notch weir for Bay 0 (GS:AB42204) and with H flumes for all other 4 bays. The period of record varied from bay to bay with the first set of measurements recorded in Oct 1976 and the last one in Feb 1992 (Table 3.1). Rainfall data were recorded during the period from May 1976 to Nov. 1997 at Bay 2 (GS: AB42206). The catchment area for these 5 contour bays varied from 0.711 Ha to 1.436 Ha (Table 3.1).

The raw data were recorded at variable time intervals for both rainfall and runoff. Both rainfall and runoff data were interpolated at 6-min intervals. This data interpolation was necessary to align rainfall and runoff, to define runoff event, and to take advantage of archived Bureau of Meteorology rainfall intensity data at 6-min intervals. To use daily flow predictions using conceptual hydrological models such as Sacramento, the 6-min rainfall and runoff data were aggregated to daily totals finishing at 9:00am for each day. For each day, the peak rainfall intensity and peak runoff rate were also extracted. An event for this report was defined as a 24-hr period (9:00am – 9:00am) for which both non-zero rainfall and runoff were recorded. For the 5 contour bays at Greenmount, the number of such events ranged from 40 to 68 (Table 3.1), and the gross runoff coefficient (ratio of the total runoff over total rainfall for these events) varied from 26% (Bay No. 2) to 37% (Bay No. 4) (Table 3.1). There were days when a small amount of runoff was recorded. Rainfall, however, had already ceased. These 'wet' days in terms of runoff were not included in this data analysis. Collectively these small runoff amounts did not contribute a great deal to total runoff from the contour bays. For instance, the total recorded runoff was 646.3 mm over the period (10.1976-02.1992) at Bay No. 5, only 2.6 mm in total on 6 occasions, or 0.4%, was recorded on 'dry' days in terms of rainfall.

Once daily rainfall and runoff totals were prepared, the daily runoff coefficient (Rc) was multiplied with the peak rainfall intensity (I_p) as a predictor of the peak runoff rate (Q_p) for each contour bay. The slope of the linear relationship between Rc I_p and Q_p would be the scaling factor (α). The scaling factor was subsequently related to catchment area for Q_p prediction.

3.3 Results on model performance

Fig. 3.1 to 3.5 show the relationship between the product of Rc and I_p and the peak runoff rate (Q_p). It can be seen that there is a consistently strong linear relationship between Rc I_p and Q_p for all the contour bays. The slope of the linear relationship is the dimensionless scaling factor (α), and its value was found to vary from 0.63 to 0.81 for the 5 contour bays (Table 3.1).

As expected, the scaling factor is inversely related to the catchment area (Fig. 3.6). The larger the catchment, the greater the storage, and the greater the attenuation of surface runoff rate, hence the smaller the scaling factor. The relationship between the catchment area and the scaling factor can be expressed as

$$\alpha = 1 - 0.2252A, \qquad r^2 = 0.86 \qquad (3.2)$$

where A is the catchment area in hectares. Note that the scaling factor is dimensionless. The relationship was then used to estimate the scaling factor from the catchment area for each contour bay, and the estimated scaling factor was used to predict the predict the peak runoff rate. The estimated values of the scaling factor are presented in Table 3.1 based on the catchment area.

The predicted and observed runoff rates are plotted in Fig. 3.7. For the combined sample size of 287 runoff events for the 5 contour bays, the overall Nash-Sutcliffe coefficient of efficiency was 0.825, and the r^2 value was 0.827. The similarity between the two performance indicators suggests that the predicted peak runoff rate was essentially unbiased. The average peak runoff rate was 6.24 mm/hr for the 287 events; while the average predicted peak runoff rate was 6.61 mm/hr, or an over-prediction of 5.9%.

Table 3.1 Summary statistics and the fitted (α) and estimated $\hat{\alpha}$ scaling factors for Greenmount contour bays at 'Marylands'.

Bay	GS	Area (Ha)	Period	N	Rc	α	r^2	$\hat{\alpha}$
0	AB42204	0.711	FEB-1982 to FEB-1992	40	29%	0.8112	0.80	0.8399
1	AB42205	1.32	OCT-1976 to FEB-1992	61	30%	0.7428	0.80	0.7027
2	AB42206	1.218	OCT-1976 to MAY-1990	68	26%	0.7955	0.89	0.7257
3	AB42207	1.157	OCT-1976 toMAY-1990	65	28%	0.6998	0.90	0.7394
4	AB42208	1.436	DEC-1978 toFEB-1991	53	37%	0.6269	0.73	0.6766

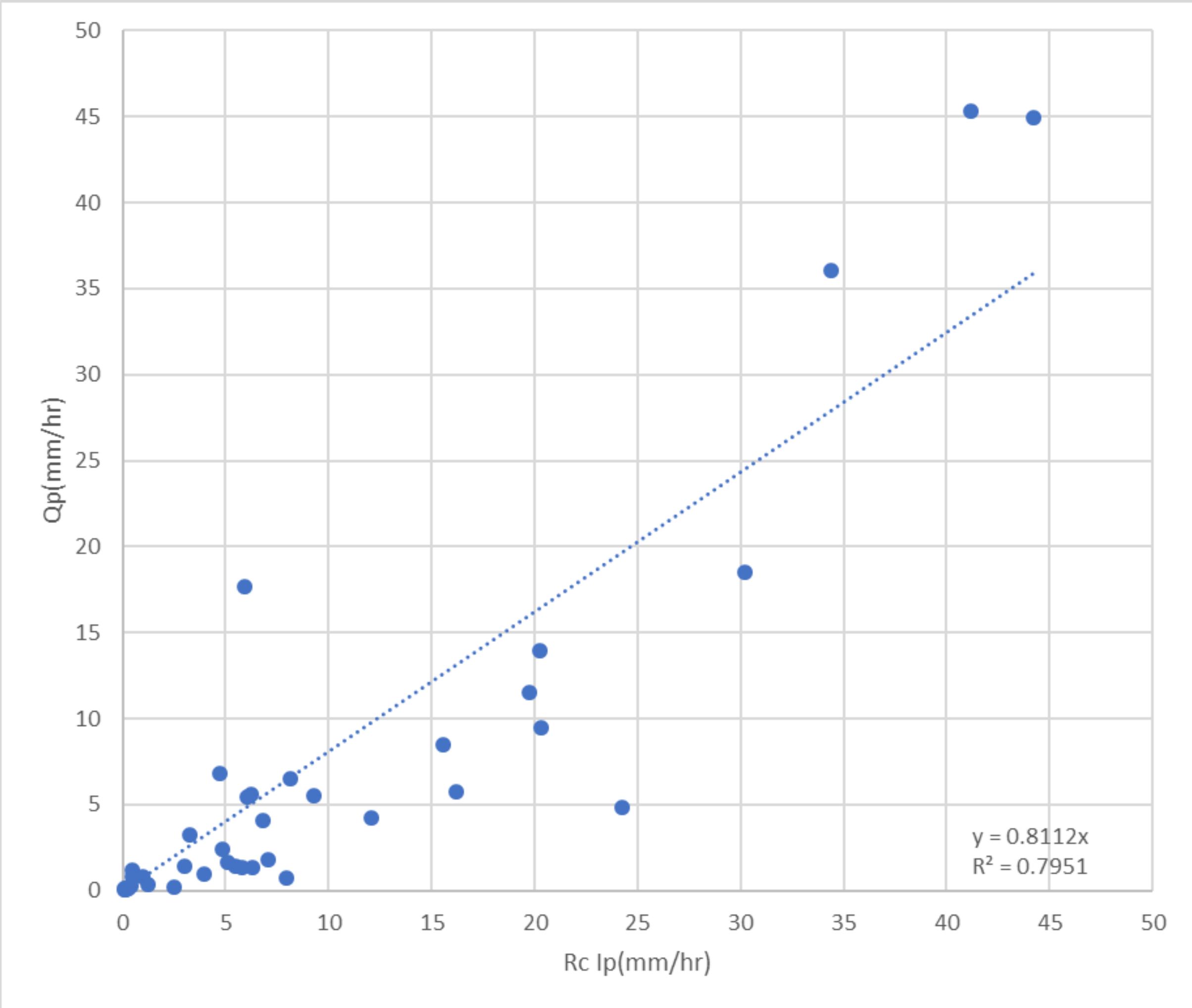

Figure 3.1 The relationship between the peak runoff rate and the product of gross runoff coefficient (*Rc*) and the 6-min peak rainfall intensity for Greenmount Contour Bay No. 0 at 'Marylands' (AB42204). The slope of the linear relationship through the origin is the scaling factor.

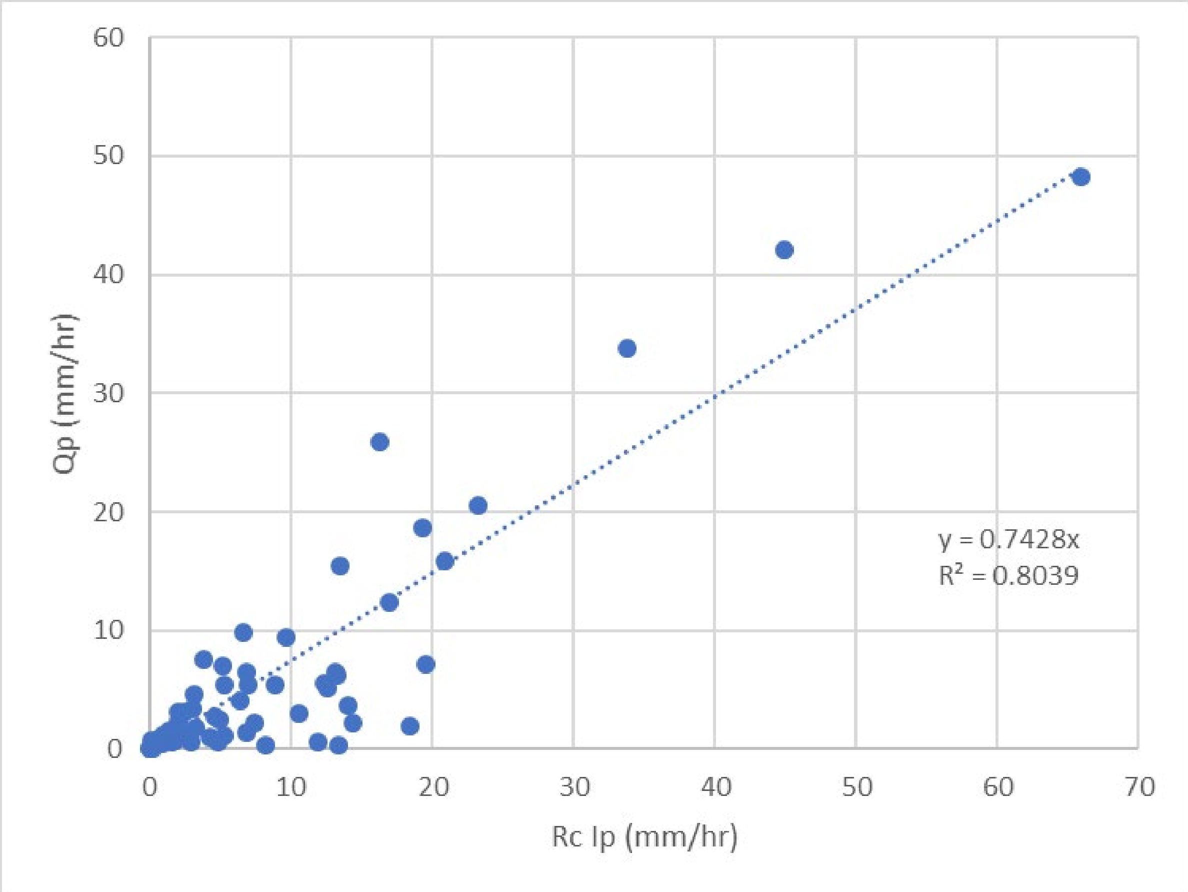

Figure 3.2 The relationship between the peak runoff rate and the product of gross runoff coefficient (*Rc*) and the 6-min peak rainfall intensity for Greenmount Contour Bay No. 1 at 'Marylands' (AB42205). The slope of the linear relationship through the origin is the scaling factor.

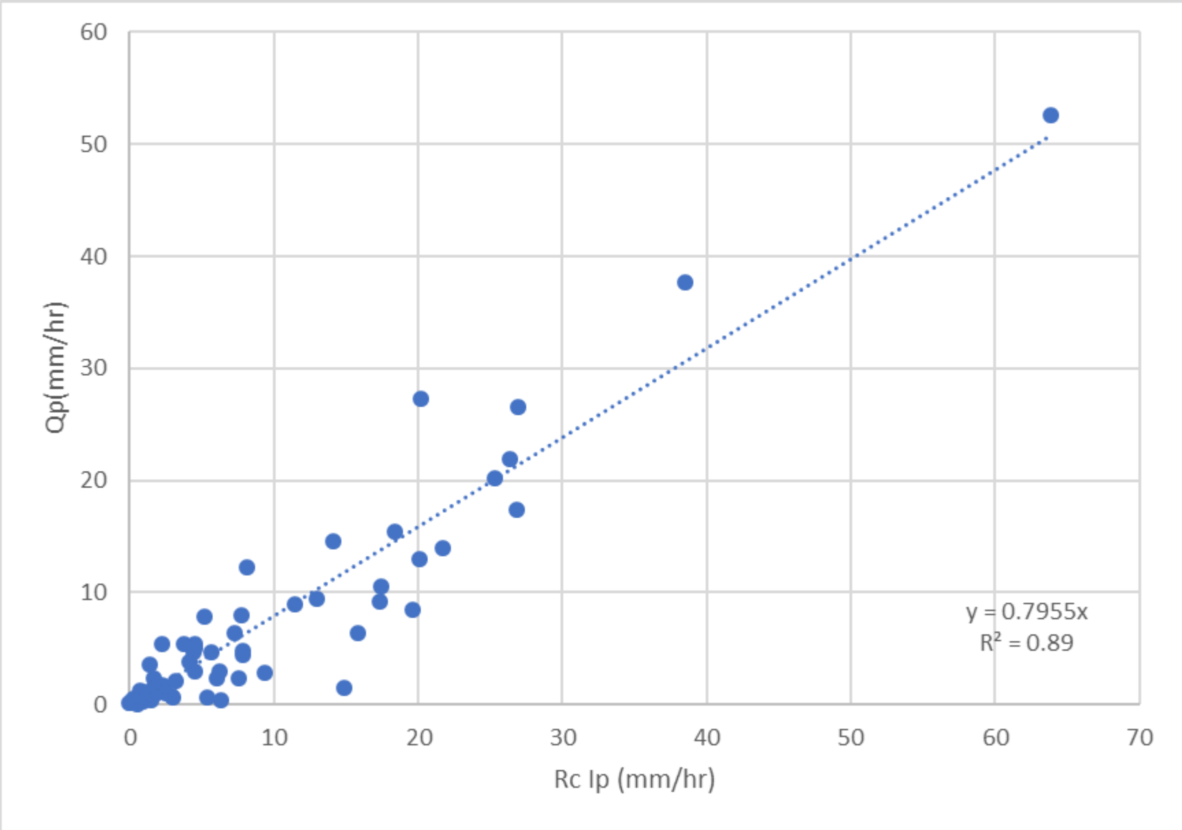

Figure 3.3 The relationship between the peak runoff rate and the product of gross runoff coefficient (*Rc*) and the 6-min peak rainfall intensity for Greenmount Contour Bay No. 2 at 'Marylands' (AB42206). The slope of the linear relationship through the origin is the scaling factor.

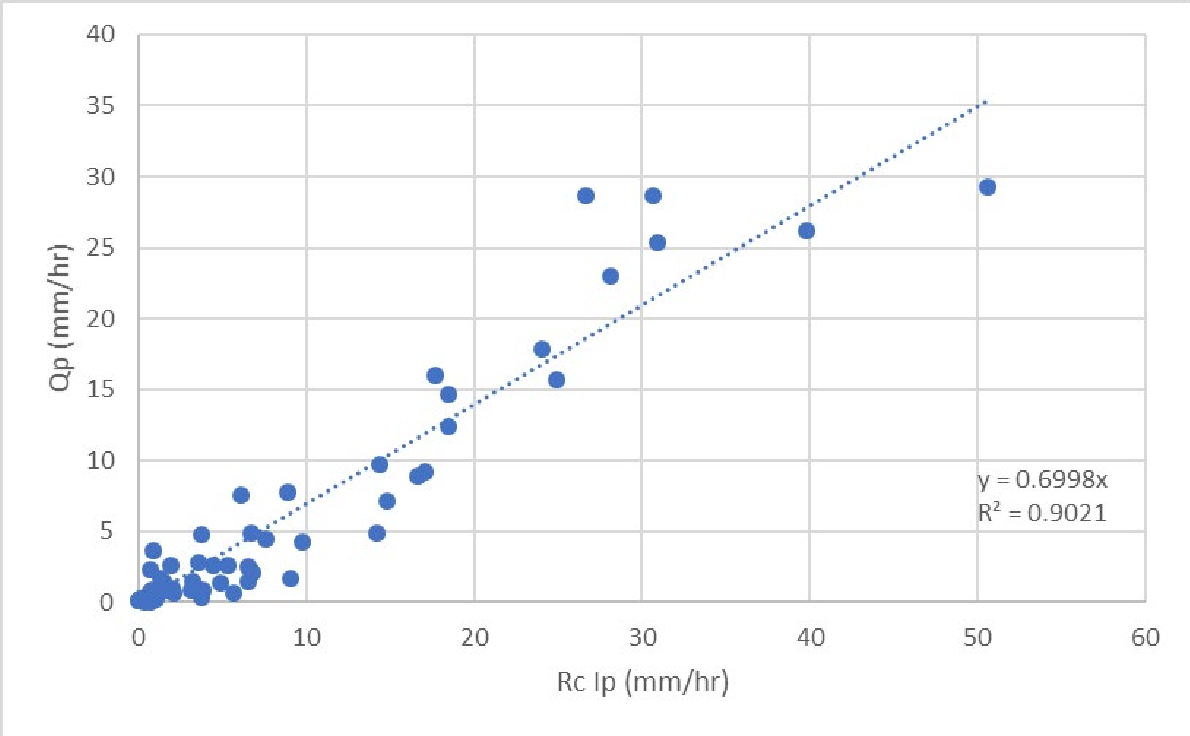

Figure 3.4 The relationship between the peak runoff rate and the product of gross runoff coefficient (*Rc*) and the 6-min peak rainfall intensity for Greenmount Contour Bay No. 3 at ‘Marylands’ (AB42207). The slope of the linear relationship through the origin is the scaling factor.

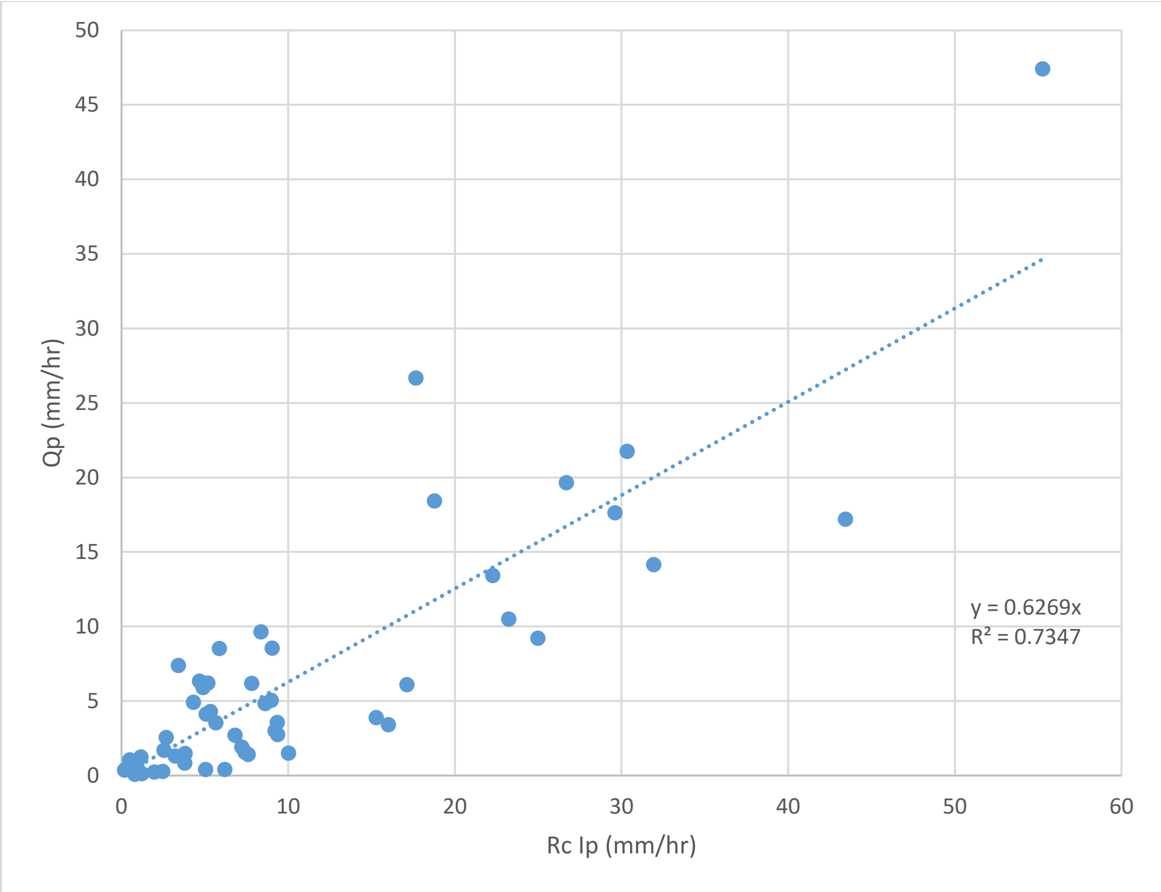

Figure 3.5 The relationship between the peak runoff rate and the product of gross runoff coefficient (*Rc*) and the 6-min peak rainfall intensity for Greenmount Contour Bay No. 4 at 'Marylands' (AB42208). The slope of the linear relationship through the origin is the scaling factor.

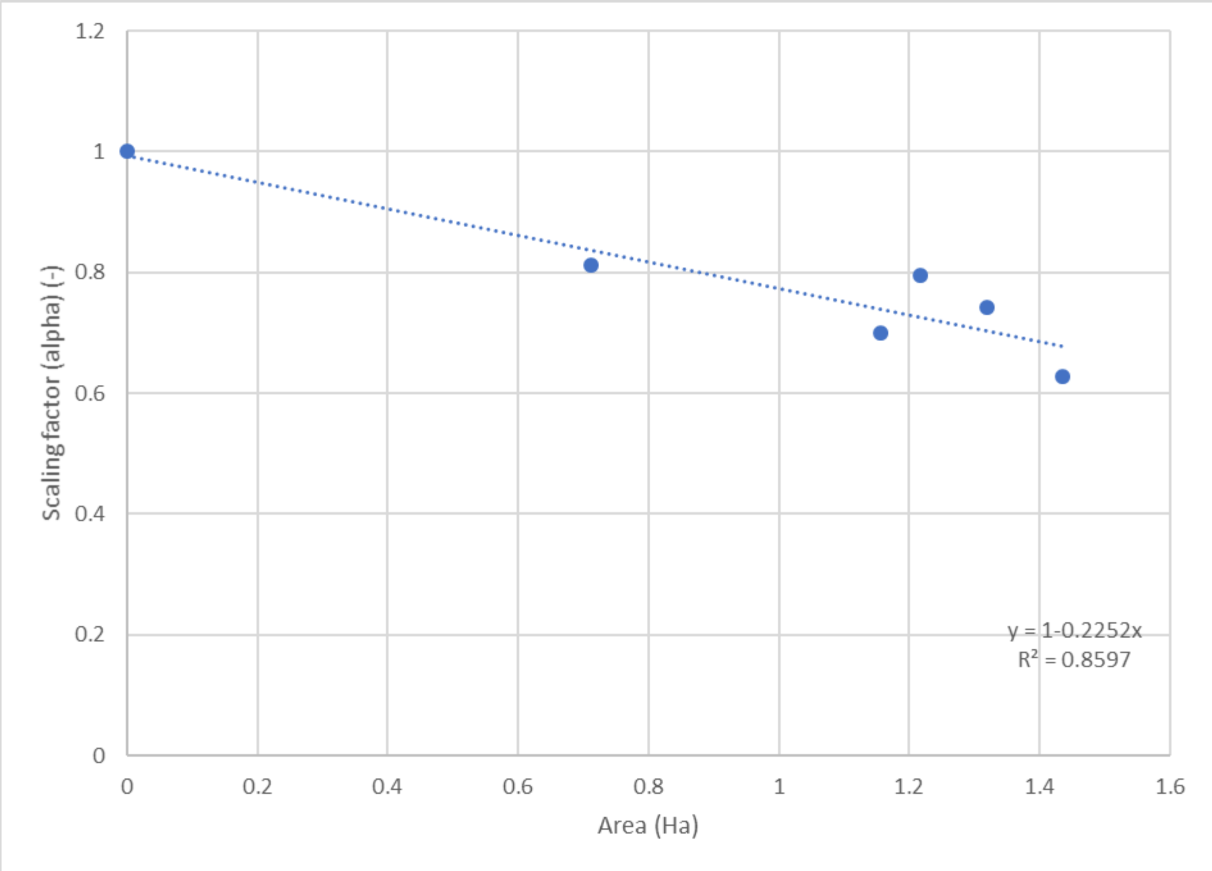

Figure 3.6 The relationship between the catchment area and the scaling factor for the 5 Greenmount contour bays.

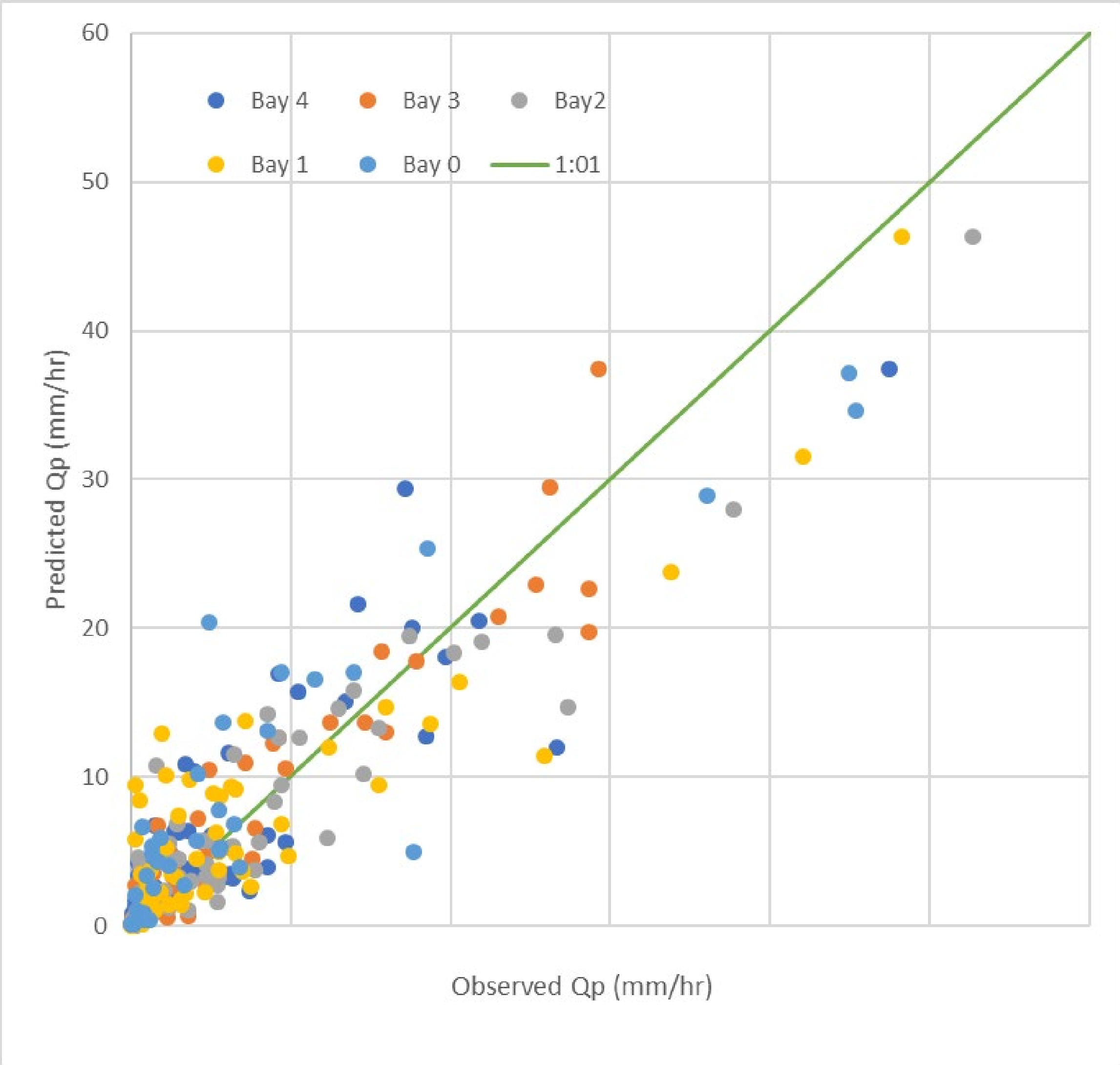

Figure 3.7 Observed and predicted peak runoff rate for the Greenmount contour bays using the area-scaling factor relationship, gross runoff coefficient, and the peak rainfall intensity.

3.4 Discussion and recommendation

There was a body of empirical evidence to support the scaling technique to predict the peak runoff rate (Yu et al., 1997; Fentie et al. 2002; and Thornton and Yu, unpublished manuscript) and results presented in this report. Given the model structure, i.e. equation (3.1), the scaling technique is particularly effective at the spatial scale where any variation in rainfall in space can be ignored. This implies applications to relatively small areas, say, less than 0.1-1km^2. This is precisely the scale where the variation in ground cover has been observed, and runoff disaggregation scheme that is sensitive to cover was developed (see Chapter 2 of the report). An interesting question to ask is why such a modelling framework where the Q_p/I_p is assumed to vary with Q_t/P_t would work for small areas. The peak runoff rate observed at the catchment outlet depends on two main processes: 1) the rate of infiltration, or loss, during periods of high rainfall intensity, and 2) flow routing to catchment outlet. Thus, the peak runoff rate, Qp, would be related to

$$I_p - f_a$$

where f_a is the actual rate of infiltration when the peak intensity occurs. In engineering hydrology, a constant loss rate is normally applied once runoff has begun. If we adopt the Green-Ampt (Green and Ampt, 1911) framework to estimate the actual rate of infiltration, the f_a term would typically approach to the saturated hydraulic conductivity. Such a scenario is presented for an arbitrarily selected rainfall event that occurred in Bundaberg between 9:00am 25/Dec/2016 and 9:00am 26/Dec/2016. The total rainfall over the 24-h period was 140.2 mm, and the peak intensity was 12.6 mm over the 6-min interval of 03:54-04:00 on 26/Dec/2016, or 126 mm h^{-1} (Fig. 3.8). For this sample event, the constant infiltration rate of 29.6 mm h^{-1} would lead to a gross runoff coefficient of 30%, a value that is typical of contour bays considered in this section. An alternative model, known as SVI (spatially variable infiltration) model (Yu et al., 1997), assuming that the actual rate of infiltration increases with rainfall intensity is given

$$f_a = I_m\left(1 - e^{-I/Im}\right)$$

where Im is a parameter, and Im can be interpreted as the spatially averaged maximum rate of infiltration. Using this approach, Im was estimated to be 55.5 mm/hr to have the same gross runoff coefficient of 30%. The constant rate of infiltration, and variable actual rate of infiltration are shown in Fig. 3.9. It can be seen that the two models behave quite differently. As rainfall intensity increases, both the runoff rate and actual infiltration rate increase. For the constant infiltration rate model, as infiltration capacity increases, the runoff coefficient decreases sharply while the peak runoff rate decrease linearly. Thus, the Q_p/I_p v. Q_t/P_t relationship is not linear as shown In Fig. 3.10. For the SVI model, f_a increases as *Im* increases, and the relationship between Q_p/I_p and Q_t/P_t is essentially linear, especially when *Rc* is relatively small as shown in Fig. 3.10. Thus, the empirical support for the scaling technique, i.e. the linear relationship between Q_p/I_p and Q_t/P_t provides further evidence to indicate that infiltration rate depends on rainfall intensity. The actual rate of infiltration increases with rainfall intensity has been observed using rainfall simulators (Flanagan et al., 1988; Foley and Silburn, 2002; Stone et al., 2008) as well as field experiments (Yu et al., 1997).

For runoff disaggregation that is sensitive to ground cover, methodology has been developed for individual 30m by 30m grid cells in Chapter 2. The area of each cell would be 900 m^2, or 0.09 Ha. Using equation (3.2) the scaling factor is estimated to be 0.9797 if the peak 6-min rainfall intensity is used to predict the peak runoff rate for the scaling technique. Smaller scaling factors would be required if the peak intensity at a larger time interval is used. Thus, the following empirical formula is recommended for 900 m^2 grid cells.

$$Q_{p6} = 0.9797 I_6 Q_t / P_t$$

where

P_t is the total rainfall for a 24-hour period (mm)

Qt is the total runoff for the corresponding 24-hr period (mm)

I_6 is the peak 6-min rainfall intensity (mm/hr) during the 24-hr period

Q_{p6} is the predicted peak 6-min peak runoff rate (mm/hr)

The scaling technique has been developed and tested so far at the plot scale (<100m^2) or contour bays (~1Ha) or small watershed (~10Ha). It is recommended that further tests of the scaling technique be undertaken for catchment areas in closer vicinity of 900 m^2 for better prediction of Q_p for individual grid cells.

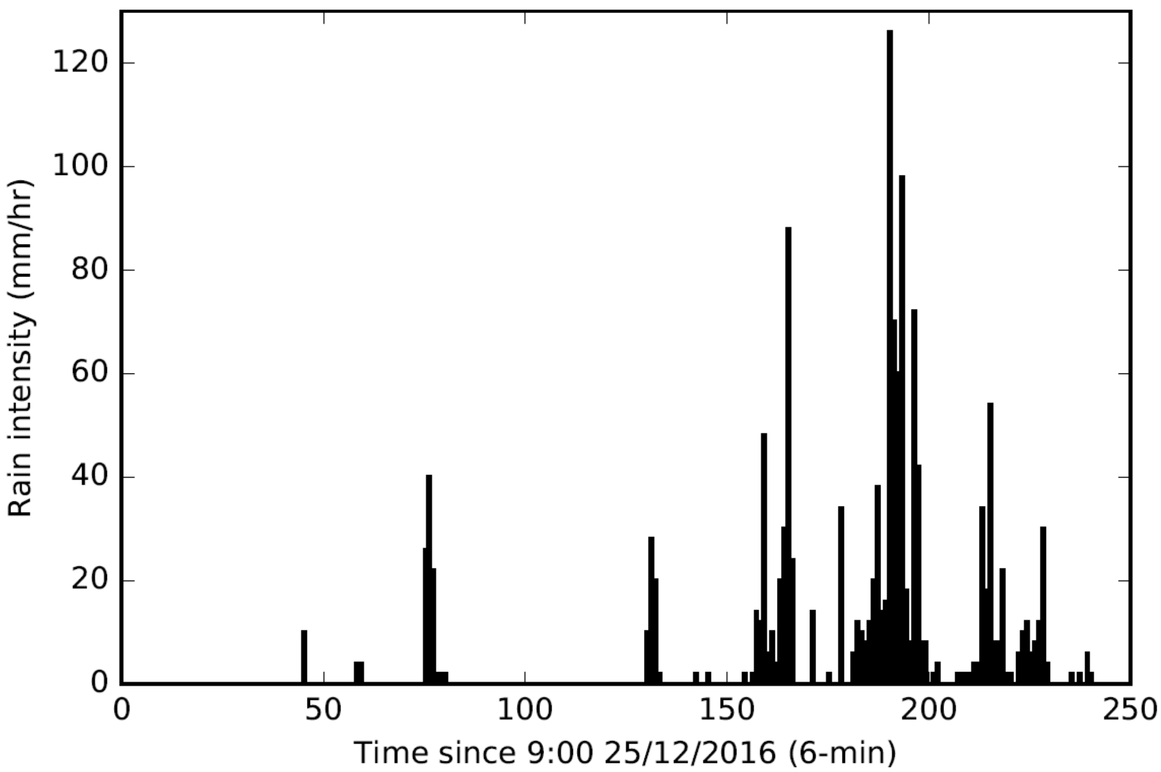

Figure 3.8 Six-min time series of rainfall intensity recorded in Bundaberg (Station No. 039128) in December 2016.

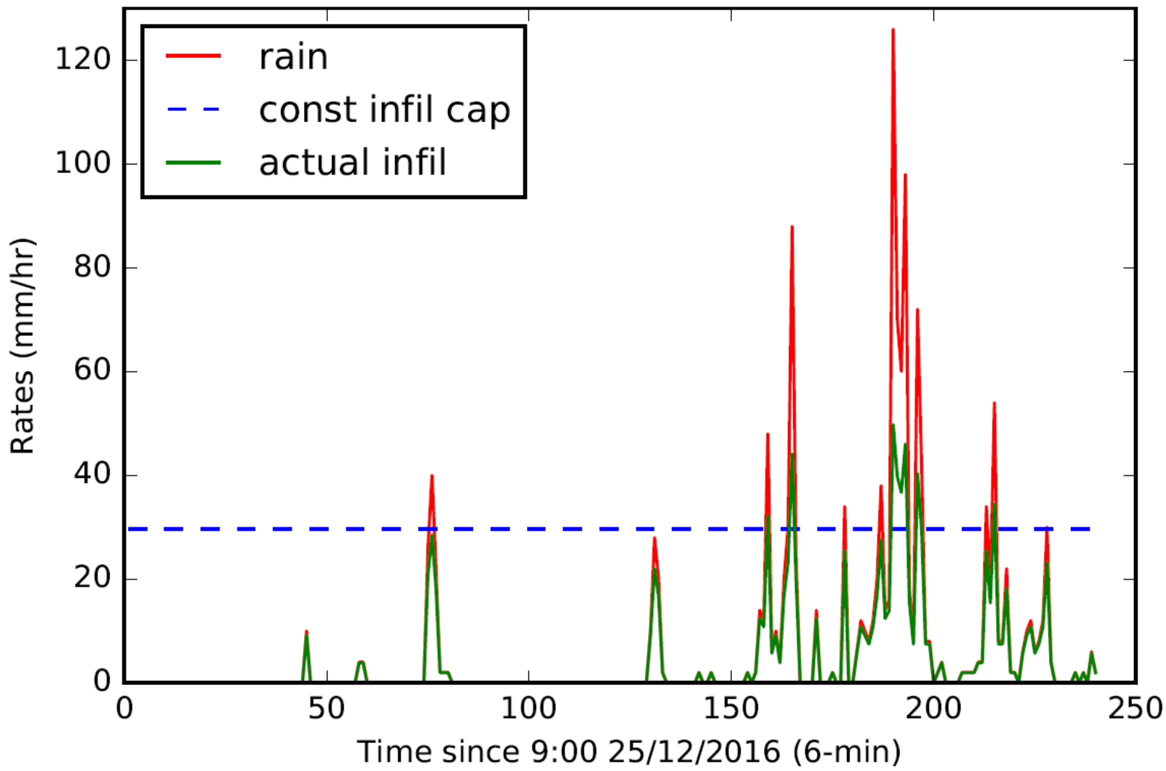

Fig. 3.9 Alternative models of infiltration and excess rainfall. Each of the two approaches would lead to a gross runoff coefficient of 30%.

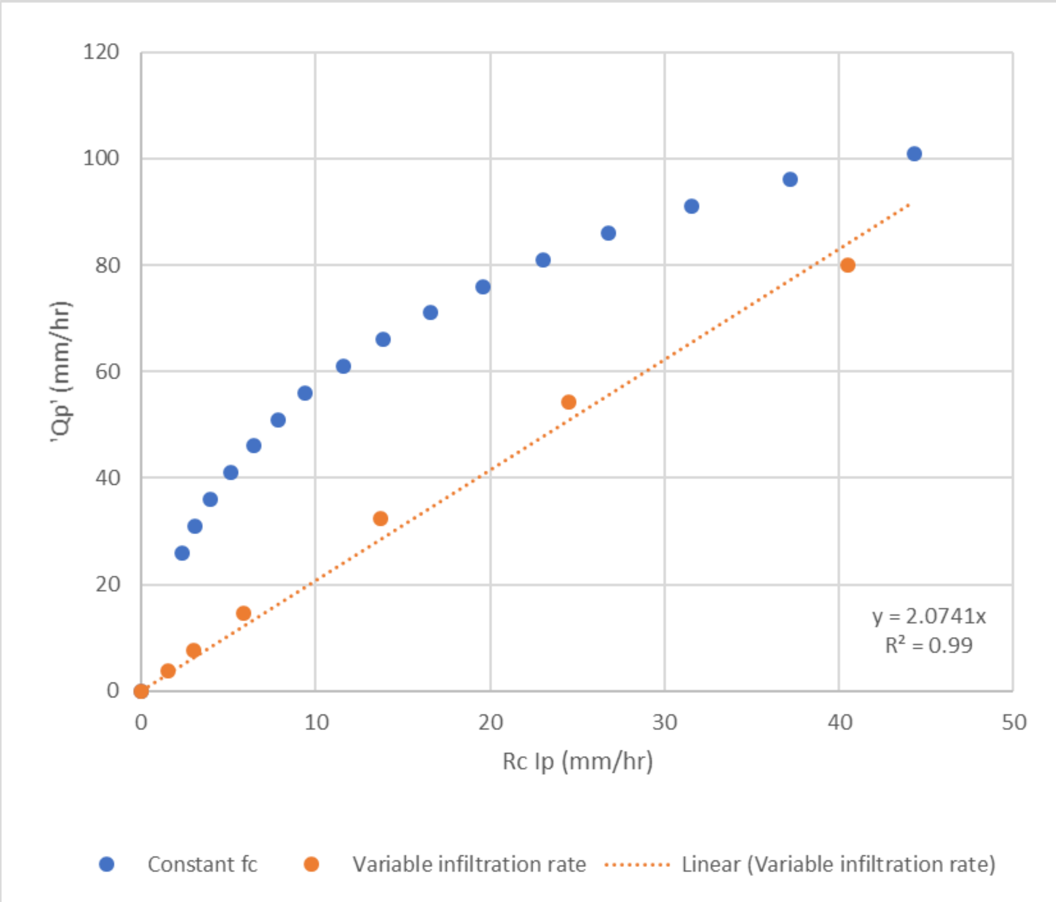

Figure 3.10 The relationship between the peak runoff rate and the product of gross runoff coefficient (*Rc*) and the peak rainfall intensity (I_p) for a range of *Rc* values using a sample rainfall event recorded in Bundaberg in December 2016. The right most points are related to *Rc* = 35% for the constant infiltration capacity model, and *Rc* = 32% for the spatially variable infiltration model.

4. Recommendations and Conclusions

To implement the Modified USLE (MUSLE) throughout the GBR catchments for improved soil erosion prediction, the following recommendations are made:

- Consultation with key stakeholders (project managers, coders, modellers, model users involved in Source/GRASP/HowLeaky) to assess, identify, and agree on temporal resolution and spatial scale at which the MUSLE is to be applied throughout the GBR catchments and possibly the whole of Queensland
- Implement the algorithm for Ip and Qp predictions in Dynamic SedNet for a GBR catchment to test and assess the impact of using MUSLE on erosion prediction for the selected catchment as distinct from using the USLE
- Ip prediction at selected temporal resolution(s) for the whole of Queensland to provide input to Dynamic SedNet for GBR catchments and possibly GRASP
- Q and Qp prediction at selected temporal resolution(s) and spatial scale(s) for the whole of Queensland to provide model input to Dynamic SedNet for GBR catchments and possibly GRASP
- Implement the algorithm for Ip and Qp predictions in HowLeaky
- Uncertainty assessment of erosion prediction due to errors in SILO-based rainfall estimates; Sacramento-based flow estimates, and in the estimated peak rainfall intensity and peak runoff rate.

Based on extensive literature review, theoretical analysis, and interpretation of observed cover and runoff data, the following conclusions can be drawn:

- Spatially distributed daily runoff amount can be predicted at 30 m resolution as an explicit function of spatially variable rainfall and ground cover provided that runoff amount at the sub-basin scale (50-100km^2) is used as a constraint on water balance.
- Users can have a choice of using either runoff coefficient as an exponential function of cover or the Curve Number as a linear function of cover; users can also choose to include a threshold level of cover beyond which the effect of cover on runoff is negligible.
- Six-min peak runoff rate can be predicted at 30 m resolution from daily rainfall and runoff amount, and the peak rainfall intensity.

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Appendix I – Changed surface condition over time in Bay 0 (AB42204) at Greenmount

The surface condition of this bay changed considerably in 1988 when the bay was planted to pasture. Prior to that, it was zero-till and fallow in summer following wheat. It was thought useful to test if the relationship between Rc Ip and Qp had changed due to changes in surface conditions.

The diagram below shows the relationship between Rc Ip and Qp based on the scaling technique for the two contrasting periods. Visually the two sets of observations appear to be well mixed. The fitted straight line in the diagram represents the best fit through the origin:

$Q_p = 0.886 I_p \frac{Q}{P}$, $R^2 = 0.89$, n = 28

using data for the period up to and including 1986.

This regression equation for cropping for the period up to 1986 is quite similar to the regression equation using all the data for the bay (Table 3.1, cropping followed by pasture, Feb-1982 to FEB-1992):

$Q_p = 0.811 I_p \frac{Q}{P}$, $R^2 = 0.80$, n = 40

Thus, different types of ground cover and different surface management practices do not affect the scaling relationship for peak runoff predictions based on this additional analysis. As argued elsewhere in the report, one of the fundamental reasons that underpins the scaling technique is that the runoff amount, or the volumetric runoff coefficient, has implicitly characterised the effect of cover on runoff. In other words, for given catchment size and time interval, Qp/Ip is proportional to Q/P given the nonlinear relationship between the actual rate of infiltration and rainfall intensity as presented in the report.

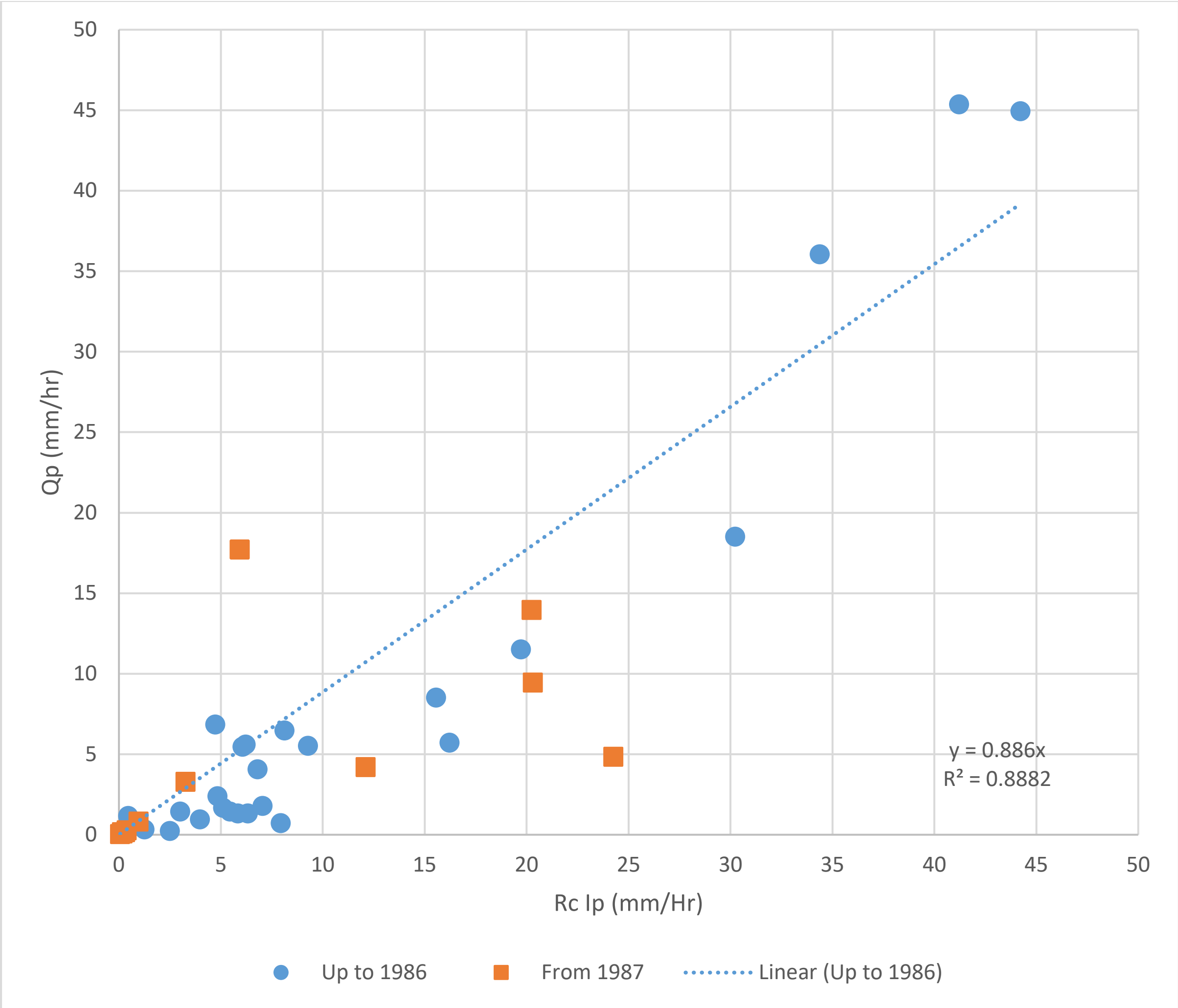

Figure A.1 The relationship between the peak runoff rate and the product of gross runoff coefficient (*Rc*) and the 6-min peak rainfall intensity for two periods of differing types of ground cover for Greenmount Contour Bay No. 0 at 'Marylands' (AB42204). The slope of the linear relationship through the origin is the scaling factor for the period up to 1986 when wheat was followed with fallow and zero-till in summer.