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Selecting curve numbers for predicting storm flow in Otago catchments

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Abstract

Predicting areas within catchments responsible for the majority of contaminant transport to surface waters requires a good estimate of flow, especially storm flow. Many process-based models require much data and are often complex to apply. Hence, we used the empirically-based curve number (CN) model to predict storm flows for rainfalls with 5-year return periods in summer (Jan-Mar), autumn (Apr-Jun) and spring (Oct-Dec) for eighteen, largely rural catchments (size, 39 to 713 km^2) in Otago. Spatially-distributed, published rainfall maps were used as input data. The winter (Jul-Sep) season was not considered, as snowfall data were not available. A frequency analysis was conducted on storm flow volumes measured at the catchment outlets to identify the 5-year return period observed during summer, autumn and spring. Curve numbers, derived from individual land cover and soil data, were area-weighted for the entire catchment (CN_{LS}). To describe the catchment conditions at the time of runoff and to predict flows comparable to those observed, CN_{LS} were altered based on three discrete antecedent moisture conditions – dry, moderate and wet. For the 5-year return period rainfalls, the predicted flows varied between 1 and 653% of observed flows. CN_{LS} corresponding to dry conditions did not predict any runoff, indicating that all rainfall was absorbed within the catchment. Generally, moderate antecedent moisture condition CN_{LS} resulted in the under-prediction of flows in all eighteen catchments, with maximum differences between observed and predicted flows in autumn and minimum differences in summer. Catchment-scale best-fit curve numbers (CN_{RF}) calculated from 5-year return period flow and rainfall data indicated that for thirteen catchments out of 18, during summer, CN_{LS} values between moderate and wet antecedent moisture conditions would have predicted flows comparable to those observed. However, under spring and autumn conditions, for nine and thirteen catchments, respectively, CN_{RF} values were greater than CN_{LS} values for wet antecedent moisture conditions, always leading to under-prediction of flows. This implied a need to revisit the curve number selection procedure for these two seasons. These results also indicated that curve number selection, and hence, its performance and suitability, is strongly related to season, and the traditional method of holding curve numbers constant for all seasons for flow prediction can poorly represent seasonal variations in flows. Evaluation of the curve number for flow prediction in Otago catchments demonstrates the need to include representation of seasonal variations in rainfall and flow conditions.

Keywords
curve numbers, runoff, modelling, CN-fitting, antecedent moisture condition

Introduction and background

Identification of runoff generation areas is central to the control of sediment and nutrient transport to surface water bodies. Pionke *et al.* (1997) termed the runoff generation areas that are critical to surface transport of sediment and nutrients to water bodies as 'critical source areas'. Gburek *et al.* (2002) and Lyon *et al.* (2004) described an approach of combining empirical and physically-based methods for predicting these critical source areas. In both studies, the empirically-based curve number (CN) method (Soil Conservation Service, 1972) was used to predict storm flow volumes. Gburek *et al.* (2002) used drainage density data, derived from topography and stream length, to predict the location and extent of source areas, while Lyon *et al.* (2004) used a topographic index. Estimated flows from curve numbers were then redistributed for predicted source areas.

The use of the curve number method for flow prediction by Gburek *et al.* (2002) and Lyon *et al.* (2004) relates to its simplicity. The curve number method is a widely used hydrological method for rainfall-runoff modelling (Fennessey, 2000). It was originally developed for event-based flood flow predictions at catchment scales (Soil Conservation Service, 1972; Garen and Moore, 2005). It has been applied, often successfully, to catchments of varying size, land use and soils, for a range of geographical locations. Smith and Williams (1980) applied the curve number method in a single-land-use 0.25 ha catchment, while Arnold *et al.* (1999) simulated a continental-scale water balance for the entire United States using a curve number-based model. Though originally developed for United States conditions, the curve number method has been used in many other countries (e.g., Boughton, 1989 in Australia; Mohammed *et al.*, 2004 in Ethiopia; Cao *et al.*, 2006 in New Zealand; Mishra *et al.*, 2006 in India). Hawkins (1979), Steenhuis *et al.* (1995) and Lyon *et al.* (2006) examined adaptation of the empirically-based curve number method to represent runoff generation processes, infiltration excess and saturation excess, to predict critical source areas at catchment scale. All these studies highlight the curve number method's versatility, adaptability and transferability across scales and regions.

When presenting a critique on this method, Ponce and Hawkins (1996) acknowledged the lack of other methods that were as easily understood or applied as curve numbers. For instance, Wilcox *et al.* (1990) compared the physically-based Green-Ampt equation and empirically-based curve number method in simulating runoff from six rangeland catchments from Texas, Oklahoma, Nebraska, Arizona and Idaho, and reported that although the physically-based method performed better than the curve number method, it was complex to use. In an alternative view, King *et al.* (1999) compared the flows simulated by the Green-Ampt equation with those of the curve number method in a 21.3 km^2 catchment in Mississippi, and concluded that the Green-Ampt method did not provide any significant gain over the curve number method. Even though the results on the effectiveness of the empirically-based curve number method over physically-based approaches have been somewhat mixed, the ease of use of the curve number method has been well established.

Application of the curve number method in New Zealand has been reported in catchments with diverse land use, size as well as topography. Cao *et al.* (2006) applied the curve number-based Soil and Water Assessment Tool (SWAT; Arnold *et al.*, 1998) in seven sub-catchments, including two mountainous sub-catchments, of Motueka catchment, with drainage areas varying from 82 to 1765 km^2. They concluded that the model performance was acceptable and could have been improved by including spatial variations in rainfall data. Watts and Hawke (2003) successfully applied the curve number method in two small coastal catchments (drainage area < 3.5 km^2) that were experiencing a rapid change in land use from rural to urban.

The goal of this study was to evaluate the selection of curve numbers for predicting flows in Otago catchments. Specifically, the curve number method was applied to predict storm flow for a 5-year return period rainfall event that occurred under different seasonal conditions in eighteen catchments in Otago. Predicted flows were compared against 5-year return period flows in these catchments. Additionally, to better understand the selection and performance of curve numbers under different seasonal conditions, catchment-scale best-fit curve numbers calculated from 5-year return period rainfall and flow data from each season were compared with catchment-scale curve numbers derived from soil and land use data.

Methods

Eighteen catchments, monitored by the Otago Regional Council for flood forecasting and management, were chosen for curve number evaluation. Figure 1 and Table 1 show the locations and areas, respectively, of these catchments. These catchments were chosen because of the availability of historical flow records. Based on flow monitoring locations (Table 1) and topography data derived from 20-m elevation contours from

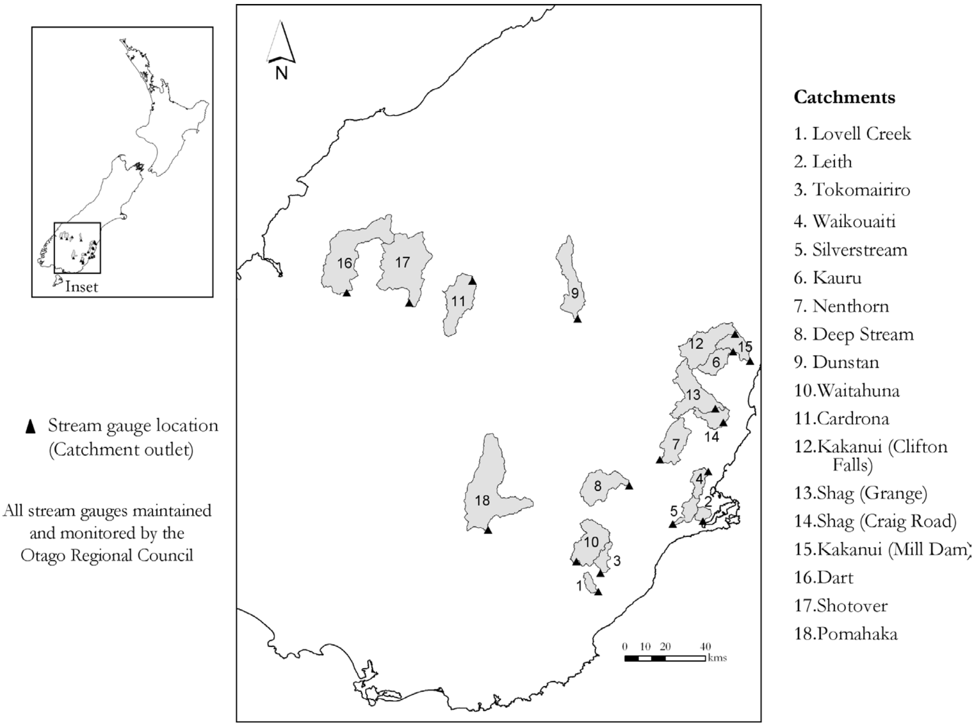

Figure 1 – Location of catchments used for the curve number selection study in Otago, New Zealand.

Table 1 – List of catchments used for the curve number selection study in Otago, New Zealand.

Catchment	Flow monitoring location Easting	Northing	Catchment area km^2	Duration of flow data available	Elevation range m (msl)
Lovell Creek	2264976	5444678	39.2	1970-80, 1999-present	18-407
Leith	2316896	5479775	42.9	1963-present	11-716
Tokomairiro	2266039	5453977	68.4	1996-present	45-636
Waikouaiti	2319570	5504389	78.8	1991-present	45-736
Silverstream	2301961	5478278	81.4	1987-present	0-738
Kauru	2331828	5563854	122.3	1992-96, 2004-present	111-1334
Nenthorn	2295574	5510353	200.4	1983-present	261-735
Deep Stream	2280352	5497333	235.5	1992-present	350-1159
Dunstan	2254680	5580380	266.4	2002-present	421-2075
Waitahuna	2254100	5459700	269.4	1992-present	88-663
Cardrona	2202600	5599200	290.5	1977-88, 2001-present	347-1879
Kakanui (Clifton Falls)	2332838	5572690	294.2	1981-present	92-1577
Shag (Grange)	2323115	5535666	320.1	1990-present	73-1479
Shag (Craig Road)	2327060	5528832	429.3	1993-present	29-1479
Kakanui (Mill Dam)	2340303	5559286	544.1	1989-present	11-1598
Dart	2140086	5593287	572.4	1996-present	288-2738
Shotover	2171205	5588146	591.2	1997-present	457-2417
Pomahaka	2210249	5475420	713.3	1992-present	177-1469

Land Information New Zealand (Land Information New Zealand – *Toitu te whenua*, 2006), the surface drainage extents and areas of the eighteen catchments were delineated and calculated, respectively, within ArcGIS (ESRI, 2001). The catchments ranged from 39.2 (Lovell Creek) to 713.3 km^2 (Pomahaka). Although the catchments have very similar land uses (forest and grassland), they varied widely in size, topography (Table 1; elevation range) and rainfall received (Table 2; 24-hour maximum, 5-year return period).

In 2004, the Otago Regional Council, in cooperation with the National Institute of Water and Atmospheric Research, published rainfall maps (24-hour maximum, 5-year return period) for the Otago region, as part of GrowOtago (Otago Regional Council, 2004). These maps were based on data from an intensive network of temporarily installed rain gauges across the region. In this study, the maps depicting 24-hour maximum, 5-year return period rainfall for summer (January-March), autumn (April-June) and spring (October-December) were used. Many of the catchments included in this study receive snowfall during winter. The published maps do not separate snowfall from rainfall. Also, many catchment-scale studies have highlighted the poor performance of the curve number method for snow-melt conditions (e.g., Peterson and Hamlett, 1998; Arnold *et al.* 1999; Fontaine *et al.*, 2002). Hence, the winter season was not included for modelling.

Storm flows were separated from stream flows using an automated base-flow separation method described by Arnold *et al.* (1995). This method uses a digital filter technique, wherein high frequency (storm flow) signal is separated from a low frequency (base flow) using a filter parameter (base flow recession). Upon delineating storm flows from base flows, storm flow volumes for individual storms were computed. A flood flow frequency analysis, as described by Jarrett (1995), was carried out for storm flow volume data, and the 5-year return period flow events for summer, autumn and spring were identified for each catchment. According to Jarrett (1995), the flood flow frequency analysis can reliably predict return periods greater than two times the length of historical record. He also indicated that the greater the amount of data, the better the prediction. Rainfall data based on published return period maps and flow data based on flow frequency analysis are listed in Table 2 for the three seasons and for all catchments. Further analyses in this paper are based on these statistically estimated 5-year return period rainfall and flow volume data.

Derivation of curve numbers

Based on land use/land cover data (AgriQuality New Zealand, 2006) and regional-scale soil data (Otago Regional Council, 2004), curve numbers were derived for various combinations of land cover and soil hydrologic group from the National Engineering Handbook (Soil Conservation Service, 1972). These curve numbers correspond to moderate antecedent moisture conditions (AMC 2). Shobani (1976; as reported by Hawkins, 1978) developed the following equations to calculate curve numbers for dry and wet antecedent moisture conditions based on curve numbers for moderate conditions:

$$CN@AMC1 = \frac{CN@AMC2}{2.334 - 0.01334 * CN@AMC2} \quad (1)$$

$$CN@AMC3 = \frac{CN@AMC2}{0.4036 - 0.0059 * CN@AMC2} \quad (2)$$

where AMC 1 represents dry catchment conditions; AMC 2, moderate conditions; and AMC 3, wet conditions (Bhuyan *et al.*, 2003). For a combination of land use and soil type, curve numbers increase from dry to wet catchment conditions. For a given rainfall, as the catchment moisture condition increases from dry to wet, an increasing curve number would result in more rainfall becoming runoff. More discussions on the definition and distinction of AMC 1, 2 and 3 can be found in Bhuyan *et al.* (2003) and McCuen (1998). Curve numbers identified for each combination of soil and land use were combined at a catchment scale to derive area-weighted catchment-scale curve number (referred to as CN_{LS} hereafter). For flow simulation using CN_{LS} values, the rainfall range data (shown in parenthesis in Table 2) was used. By applying CN_{LS} values to each rainfall zone, runoff was predicted and totalled at a catchment scale. Flows were predicted for the three discrete antecedent moisture conditions.

In order to obtain the best-fit curve number (referred to as CN_{RF} hereafter) specific to catchment conditions, seasons and storm event, curve numbers were calculated from 5-year return period rainfall and flow data in each catchment. For the purpose of CN_{RF} calculation, it was assumed that the 5-year return period rainfall event would result in a flow event of same return period. Hawkins (1984) reported the successful use of this approach of calculating best-fit curve numbers from rainfall and flow data in 110 small catchments (< 1 km^2) under single land use – pastoral agriculture, forest and rangeland. To calculate curve numbers from rain and flow data, the following formulae described by Hawkins (1984) were used:

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \quad (3)$$

$$CN_{RF} = 25400/(254 + S) \quad (4)$$

where, S is the site storage parameter in mm, P and Q are rainfall and storm flow depths, respectively, in mm, and CN_{RF} is the curve number that would best fit the specific catchment conditions, based on rainfall and flow data used. CN_{RF} is derived at catchment scale, and thus, represents combined, not individual land uses and soil types. The site storage parameter *S* is used to define the amount of rainfall required for runoff to start. To predict runoff using the curve number

Table 2 – Statistically-estimated 5-year return period rainfall and flow data for the selected Otago catchments. Rainfall data based on GrowOtago precipitation maps. Flow data based on flood frequency analysis of observed flow volumes at the respective catchment outlets.

Catchment	5-year return period rainfall† (mm) Summer (Jan-Mar)	Autumn (Apr-Jun)	Spring (Oct-Dec)	5-year return period storm flow (mm) Summer	Autumn	Spring
Lovell Creek	51 (48-58)	40 (38-48)	41 (35-48)	3.5	10.9	6.7
Leith	81 (58-175)	45 (38-65)	47 (39-53)	22.8	26.0	14.6
Tokomairiro	46 (38-53)	47 (38-55)	45 (43-48)	11.4	14.2	9.6
Waikouaiti	88 (68-175)	37 (25-48)	40 (35-48)	16.1	8.4	9.2
Silverstream	64 (33-175)	43 (25-65)	46 (33-53)	22.4	11.0	11.1
Kauru	71 (63-175)	24 (19-43)	49 (39-53)	10.2	8.4	13.8
Nenthorn	42 (33-73)	25 (21-38)	37 (35-39)	5.8	4.2	5.8
Deep Stream	50 (33-63)	43 (25-55)	33 (27-43)	14.1	19.1	19.2
Dunstan	65 (38-175)	36 (23-65)	49 (37-65)	6.1	3.2	3.9
Waitahuna	45 (33-53)	43 (38-55)	41 (37-48)	6.5	4.9	7.5
Cardrona	73 (43-175)	32 (23-65)	51 (37-65)	3.9	5.2	8.1
Kakanui (Clifton Falls)	66 (33-175)	25 (19-48)	46 (35-58)	10.7	8.1	10.2
Shag (Grange)	48 (33-175)	25 (21-48)	42 (35-58)	3.6	2.6	5.1
Shag (Craig Road)	53 (33-175)	25 (21-48)	41 (35-58)	3.6	2.7	2.5
Kakanui (Mill Dam)	64 (33-175)	24 (19-48)	45 (33-58)	13.5	8.7	11.5
Dart	179 (88-250)	74 (23-95)	164 (125-175)	93.5	72.4	98.5
Shotover	144 (63-250)	54 (25-95)	98 (58-175)	15.1	18.3	23.4
Pomahaka	58 (33-175)	46 (25-65)	48 (37-58)	15.7	17.7	20.2

† Area-weighted rainfall. Numbers shown in the parenthesis indicate the range of rainfall recorded within the catchment.

method, the rainfall has to be greater than 0.2 times the site storage parameter *S* (Hawkins, 1984). Steenhuis *et al.* (1995) indicated that holding the site storage parameter *S* as a constant proportion of rainfall might not be valid under varying catchment moisture conditions. However, in the absence of any guidance in selecting a site storage parameter for New Zealand conditions, the original assumption (0.2 times rainfall) was used in this study.

Also, based on CN_{RF}, the antecedent moisture conditions at the time of runoff simulation were deduced using the following formulae described by Bhuyan *et al.* (2003):

For $CN_{RF} < CN_{LS}$ at moderate antecedent moisture conditions (AMC 2),

AMC at the time of runoff

$$= 1 + \frac{(CN_{RF} - CN_{LS}@AMC1)}{(CN_{LS}@AMC2 - CN_{LS}@AMC1)} \quad (5)$$

For $CN_{RF} > CN_{LS}$ at moderate antecedent moisture conditions (AMC 2),

AMC at the time of runoff

$$= 2 + \frac{(CN_{RF} - CN_{LS}@AMC2)}{(CN_{LS}@AMC3 - CN_{LS}@AMC2)} \quad (6)$$

Catchment-scale antecedent moisture conditions for CN_{RF} and CN_{LS} were compared to better understand the selection and performance of curve numbers.

For each catchment, observed and predicted flows from various seasons were compared using the statistical measure, deviation of runoff volume, or D_v, described by Martinec and Rango (1989).

$$D_v = [(\text{Observed} - \text{Predicted})/\text{Observed}]*100 \quad (7)$$

D_v, expressed in percentage, is zero when the observed and predicted flows perfectly match each other; positive, when the observed flows are under-predicted; and negative, when the observed flows are over-predicted.

Results and discussion

Rainfall distribution and resultant storm flows varied widely among the seasons across the region (Table 2). Of the three seasons considered, the widest range of rainfall was in summer, which also had the greatest rainfall with a 5-year return period; autumn had the least. However, the flows did not always follow the same trend as rainfall. For instance, in the Shotover catchment, which received almost three times more rainfall in summer than in autumn, flow depth was greater in autumn than in summer. Such significant differences in flows with seasons from New Zealand catchments have been reported in the past (Atkinson *et al.*, 2002).

One of the key assumptions made in this study was that the 5-year return period rainfall event would result in a flow event of same return period. Based on a rank correlation procedure, Larson and Reich (1973; as reported by Haan and Schulze, 1987) concluded that the ranks of annual floods and annual storm rainfalls have a central tendency toward equality. Haan and Schulze (1987) suggested that a mismatch in the recurrence intervals of rainfall and flow could largely be attributed to antecedent conditions. In this study, by narrowing down the return period calculations to 3-month long seasons, the potential mismatch due to extreme antecedent conditions was reduced. Jarrett (1995) suggested that the uncertainty associated with the derivation of return period data could be reduced by using multiple years of observed data. In this study, thirty-one years of rainfall and 4 (Dunstan) to 44 years (Leith) of flow data were used to statistically estimate 5-year return period rainfall and flow data.

Table 3 presents results on the comparison of observed and CN_{LS}-predicted flows. Catchment-scale CN_{LS} values for moderate and wet antecedent moisture conditions are listed in Table 4. For the majority of catchments, and for the three seasons, a large site storage parameter (*S*) during dry periods resulted in no or negligible runoff under dry antecedent moisture conditions. Hence, they are not included in Table 3. Such 'no-flow' conditions were observed in a few catchments for moderate antecedent moisture conditions also. Kauru and Kakanui (Clifton Falls) catchments in autumn did not predict any flows when moderate antecedent moisture conditions CN_{LS} were applied.

The wide range in D_v values for different seasons for the same catchment indicated the variable fit of CN_{LS} values. For example, in the Lovell Creek catchment, the catchment-scale wet antecedent moisture condition CN_{LS} value was 77 (see Table 4). In this catchment, the predicted flow was 219% greater than observed in summer (Table 3), but the observed and predicted flows were within 1% of each other for the same antecedent moisture conditions in spring. Thus, the catchment-scale CN_{LS} value was sufficient to predict observed flows in spring, but over-predicted the flows in summer and under-predicted flows in autumn. Similarly, in the Cardrona catchment, observed flows were over-estimated in summer (wet antecedent moisture condition CN_{LS}, 80, Table 4; wet antecedent moisture condition D_v, -653%, Table 3), while the observed and CN_{LS} predicted flows were within 10% of one-another in autumn (wet antecedent moisture condition D_v, 10%). Because curve numbers were not altered with seasons, the predicted flows failed to reflect the differences in flow variations with seasons.

In the Leith and Silverstream catchments, positive D_v values for all seasons and for both moderate and wet antecedent moisture

Table 3 – Performance of the curve number method based for 5-year return period storm events during summer, autumn and spring in the selected Otago catchments.

Catchment	Dv† Summer Moderate AMC	Dv† Summer Wet AMC	Dv Autumn Moderate AMC	Dv Autumn Wet AMC	Dv Spring Moderate AMC	Dv Spring Wet AMC
Lovell Creek	68	-219	99	45	97	-1
Leith	86	15	100	86	98	58
Tokomairiro	82	-22	84	-4	82	-36
Waikouaiti	-2	-167	94	10	92	-2
Silverstream	83	19	98	41	96	27
Kauru	87	-35	No flow predicted	99	100	66
Nenthorn	70	-109	99	23	89	76
Deep Stream	82	-7	92	41	100	71
Dunstan	2	-237	96	-35	81	-147
Waithuna	61	-125	58	-171	76	-67
Cardrona	-150	-653	97	10	75	-70
Kakanui (Clifton Falls)	81	-28	No flow predicted	95	100	54
Shag (Grange)	66	-180	100	58	94	-36
Shag (Craig Road)	16	-311	100	40	82	-202
Kakanui (Mill Dam)	81	-12	100	95	99	51
Dart	43	-2	94	75	57	17
Shotover	-116	-359	94	49	53	-47
Pomahaka	78	-6	95	48	83	18

† D_v or deviation of runoff volume = [(observed flow – predicted flow)/observed flow], expressed in percent. Positive D_v – observed flows under-predicted; negative D_v – observed flows over-predicted. AMC – antecedent moisture conditions

conditions indicated that the CN_{LS} values under-predicted the observed flows. Of all the eighteen catchments considered in this study, these two catchments have the largest proportion of urban areas (2.6% in Leith and 1.0% in Silverstream), and almost all these urban areas are concentrated adjacent to catchment outlets. In other catchments, urban land use is scattered and accounts for less than 0.1% of catchment area. Fast, large-scale conversion of rainfall to runoff from these concentrated urban areas could have influenced the flows measured at these catchment outlets.

Under moderate antecedent moisture conditions, except for summer in the Waikouaiti, Cardrona and Shotover catchments, positive D_v values for all three seasons and for all catchments indicated that observed flows were always under-predicted (Table 3). In some catchments, such as the Dart and Pomahaka, the change from negative to positive D_v values were observed for one season (Table 3). In some others (e.g., Tokomairiro, Deep Stream, Dunstan, Waitahuna, Pomahaka), this was observed for all three seasons. The change in polarity of the D_v values between moderate and wet antecedent moisture conditions implied that the best-fit curve number for that particular storm and season lie in between those two antecedent conditions.

Varying curve numbers based on antecedent moisture conditions was further investigated to better understand the catchment conditions depicted by CN_{LS} and CN_{RF} values. Based on the CN_{LS} values, the antecedent moisture conditions corresponding to CN_{RF} values were estimated using equations 5 and 6, described by Bhuyan *et al.* (2003) (Table 4). Wet antecedent moisture condition CN_{LS}

Table 4 – Comparison of catchment-scale curve numbers – CN_{LS} vs. CN_{RF} for the selected Otago catchments.

Catchment	CN_{LS}[1] (based on land use and soil hydrologic group) Moderate AMC	Wet[2] AMC	CN_{RF}[3] (based on 5-year return period storm flows) Summer	Autumn	Spring	Antecedent moisture conditions[4] Summer	Autumn	Spring
Lovell Creek	58	77	28	64	33	0.3	2.3	0.6
Leith	56	73	87	93	91	–[5]	–	–
Tokomairiro	64	82	69	95	78	2.3	–	2.8
Waikouaiti	63	81	74	91	78	2.6	–	2.8
Silverstream	57	76	76	94	78	3.0	–	–
Kauru	49	68	60	77	83	2.6	–	–
Nenthorn	65	83	69	74	75	2.2	2.5	2.6
Deep Stream	63	81	85	98	92	–	–	–
Dunstan	59	76	66	68	68	2.4	2.5	2.5
Waitahuna	67	83	69	86	78	2.1	–	2.7
Cardrona	61	80	68	86	78	2.3	–	2.9
Kakanui (Clifton Falls)	51	70	40	71	53	1.4	–	2.1
Shag (Grange)	58	76	58	68	71	2.0	2.6	2.7
Shag (Craig Road)	60	78	68	65	67	2.5	2.3	2.4
Kakanui (Mill Dam)	54	73	61	83	84	2.3	–	–
Dart	53	70	74	94	92	–	–	–
Shotover	52	71	69	84	96	2.9	–	–
Pomahaka	59	77	73	92	86	2.8	–	–

[1] CN_{LS}; catchment-scale area-weighted curve number based on land use and soils from Soil Conservation Service (1972).
[2] Wet antecedent moisture condition curve numbers calculated from moderate antecedent moisture condition curve numbers using equation 2 presented in the text.
[3] CN_{RF}; catchment-scale curve number based on statistically-estimated 5-year return period rainfall and flow data
[4] Antecedent moisture condition deduced based on CN_{RF} values using equations 5 and 6 presented in the text.
[5] CN_{RF} > AMC 3 CN_{LS}, no AMC calculated.

values shown in Table 4 are the maximum attainable curve number, based on moderate antecedent moisture condition CN_{LS} values selected from the Soil Conservation Service curve number table. Hence, when the best-fit curve number (CN_{RF}) values were greater than wet antecedent moisture condition CN_{LS} values, no antecedent moisture condition deductions were made. Under such conditions, the moderate antecedent moisture condition CN_{LS} values should be increased so that the CN_{RF} stays within the defined antecedent moisture condition range. For three catchments in summer, 13 catchments in autumn and 10 catchments in spring, the CN_{RF} values were greater than the wet antecedent moisture condition CN_{LS} values. In other words, the curve numbers derived from the Soil Conservation Service curve number table based on soil and land use data would always under-predict the observed flows for these catchments even under the wettest antecedent moisture conditions (e.g., Shag, Dart). Hawkins (1993) concluded that the selection of curve numbers from the Soil Conservation Service curve number table based on soil and land use data can lead to inaccuracies. He indicated that curve numbers derived for traditional agricultural soils are the most successful, while the curve numbers derived for forested catchments can be the least successful. For the forested Otago catchments used here, the errors in curve number selection based on soils and land use could have led to differences in flow predictions. While Hawkins (1993) did not indicate whether the curve number selected based on soils and land use tend to over-predict or under-predict flows, in case of the 18 Otago catchments tested, the results indicate that the observed flows are generally over-predicted in summer and under-predicted in autumn and spring.

Antecedent moisture condition deductions for CN_{RF} values shown in Table 4 indicate that, for the majority of catchments and for three seasons, with the exception of Lovell Creek catchment in summer and spring and Kakanui (Clifton Falls) catchments in summer, the best-fit curve numbers (CN_{RF}) were between moderate and wet antecedent moisture conditions. Observations by Caruso (2002) in Otago catchments indicate that antecedent moisture conditions in summer could best be defined between dry to moderately wet. GrowOtago soil moisture data indicated that in many of these catchments, the available water is low to moderate throughout the year (2.5 to 7.5 cm of available water within top 90 cm of soil; Otago Regional Council, 2004). This indicates that the application of curve numbers to antecedent moisture conditions greater than moderate might not be representative. However, the antecedent moisture conditions derived based on CN_{RF} values shown in Table 4 indicate moderate to wet catchment conditions for the majority of catchments and for three seasons, except for those catchments where antecedent moisture condition CN_{LS} values were smaller than CN_{RF}. However, it should be noted the antecedent moisture conditions corresponding to the CN_{RF} values shown in Table 4 is related to CN_{LS} values chosen from the Soil Conservation Service curve number table, and are not a true reflection of catchment conditions. Thus, when the catchment-scale CN_{LS} is altered, the antecedent moisture condition corresponding to the CN_{RF} value would change.

During autumn and spring seasons, application of wet antecedent moisture condition curve numbers does not reflect the low to moderate moisture conditions existing in these Otago catchments. A review of literature on curve number selection indicated that application of curve numbers corresponding to wet antecedent moisture conditions might be unrealistic. Bhuyan *et al.* (2003) examined curve number calibration in the sub-humid Midwest United States and concluded that storm flows for most storms were over-predicted when moderate antecedent moisture condition curve numbers were used. They concluded that curve numbers corresponding to AMC 1.5 (between dry and moderate antecedent moisture conditions) best predicted the storm flows for most storms. Bhuyan *et al.* (2003) conducted their curve number calibration study in predominantly agricultural catchments, while the Otago catchments are largely forested. Added to the differences in land use, differences in climatic region (sub-humid Midwest United States versus temperate Otago, New Zealand) could also have resulted in different curve number predictions.

Table 5 presents the moderate antecedent moisture condition CN_{RF} values derived using equation 2, from CN_{RF} values shown in Table 4. It was assumed that the CN_{RF} values presented in Table 4 represent wet antecedent moisture conditions. Also, presented in Table 5 is the percentage difference between CN_{LS} and CN_{RF} values for moderate antecedent moisture conditions. For the majority of catchments, a negative percentage difference indicated the moderate antecedent moisture condition CN_{LS} values selected based on soil and land use data were smaller than they

Table 5 – Comparison of CN_{LS} and CN_{RF} moderate antecedent moisture condition curve number values for the selected Otago catchments.

Catchment	CN_{LS}	CN_{RF} † Summer	CN_{RF} † Autumn	CN_{RF} † Spring	Difference between CN_{LS} and CN_{RF} (%)‡ Summer	Difference between CN_{LS} and CN_{RF} (%)‡ Autumn	Difference between CN_{LS} and CN_{RF} (%)‡ Spring
Lovell Creek	58	13	44	15	78	24	74
Leith	56	70	79	75	-25	-41	-34
Tokomairiro	64	49	82	59	23	-28	8
Waikouaiti	63	54	75	58	14	-19	8
Silverstream	57	56	80	58	2	-40	-2
Kauru	49	40	57	65	18	-16	-33
Nenthorn	65	49	54	55	25	17	15
Deep Stream	63	65	87	76	-3	-38	-21
Dunstan	59	46	48	48	22	19	19
Waitahuna	67	49	69	58	27	-3	13
Cardrona	61	48	69	58	21	-13	5
Kakanui (Clifton Falls)	51	20	41	33	61	20	35
Shag (Grange)	58	38	48	51	34	17	12
Shag (Craig Road)	60	48	45	47	20	25	22
Kakanui (Mill Dam)	54	41	65	64	24	-20	-19
Dart	53	54	80	76	-2	-51	-43
Shotover	52	49	66	84	6	-27	-62
Pomahaka	59	39	57	53	34	3	10

† CN_{RF} values for moderate antecedent moisture conditions were derived by trial-and-error using equation 2 in the text. CN_{RF} values presented in Table 4 were assumed to correspond to wet antecedent moisture conditions.

‡ Difference (%) = $(CN_{LS} - CN_{RF})/CN_{LS}$; Positive value, CN_{LS} greater than CN_{RF}; negative value, CN_{LS} less than CN_{RF}

should have been. Only for four catchments in summer (Silverstream, Deep Stream, Dart, Shotover), two in autumn (Waitahuna, Shotover), and five in spring (Tokomairiro, Waikouaiti, Silverstream, Cardrona, Pomahaka), were the differences between the CN_{LS} and CN_{RF} values ≤10%. For the majority of catchments in summer, larger CN_{LS} values than CN_{RF} values resulted in over-prediction of observed flows. On the other hand, in autumn, smaller CN_{LS} values than CN_{RF} values resulted in under-prediction of flows.

Procedures such as calculating the curve numbers based on rainfall and flow data, as described here, may improve the catchment-scale curve numbers, though curve numbers for individual soil-land use combinations remain unexamined. Curve numbers of individual combinations of soils and land use can be altered so that the catchment-scale curve number (CN_{LS}) matches the best-fit curve number (CN_{RF}). Such a procedure should also take into account seasonal differences in catchment response to rainfall events. As indicated earlier with CN_{LS} values, the range in CN_{RF} values for different seasons highlighted the variability in curve numbers with season for the same catchment. For instance, in the Deep Stream catchment, the summer CN_{LS} values closely matched the CN_{RF} values (3% difference between them, Table 5), while the CN_{LS} values vastly differed from CN_{RF} for autumn and spring; by 38 and 21%, respectively.

Equations 3 and 4 used to calculate CN_{RF} account for rainfall and rainfall-induced flow only. However, in catchments such as the Dart, which can potentially receive snowfall at high altitudes at any time during the year, the resulting flows could be a combination of runoff from rainfall and rainfall-induced snow melt. For instance, during the autumn season in the Dart catchment, the 5-year return period rainfall and flow were 74 and 72.4 mm, respectively (Table 2). This flow might be an unknown combination of runoff from rainfall and rainfall-induced snow melt. Thus, the application of equations 3 and 4 to calculate best-fit curve numbers might lead to inaccuracies. In such catchments, data on snow melt would be essential to improve the curve number prediction.

Wide differences observed in flows with seasons, and hence, CN_{RF} values, are well in agreement with catchment-scale flow observations by Atkinson *et al.* (2002) in New Zealand catchments and Pionke *et al.* (1997, 2000) in the United States catchments. Occurrence of large and spatially widely-distributed rainfall events and small flow events in summer, and small and spatially less widely-distributed rainfall events and large flow events in autumn and spring, indicate strong seasonal variability in the hydrological behaviour of these catchments. By including the seasonal, spatially-distributed rainfall data and flow data from other return periods, the curve number selection can be improved and best-fit curve numbers could be derived for these Otago catchments. Such a model development would be the critical first step toward the dual-approach model suggested by Gburek *et al.* (2002) and Lyon *et al.* (2004) for predicting critical source areas.

Conclusions

The United States Soil Conservation Service curve number (CN) method was applied to eighteen Otago catchments to predict flood flows for 24-hour maximum, 5-year return period rainfall events occurring in summer, autumn and spring. Curve numbers were altered between dry, moderate and wet antecedent moisture conditions to reflect catchment moisture conditions at the time of runoff as well as to match observed and predicted flow volumes. Under dry conditions the curve number model predicted negligible or no flows in all catchments. In most catchments, for all three seasons, curve numbers related to moderate antecedent moisture conditions appeared to predict significantly less flow than observed (predicted flows 2 to 100% less than observed). This result was found to contrast with observations from sub-humid, agricultural catchments of the Midwestern United States, where curve numbers related to AMC 1.5 (dry to moderate antecedent moisture conditions) generated flows comparable to those observed. In forested Otago catchments, curve numbers related to moderate antecedent moisture conditions and greater were needed to generate observed flows. For thirteen catchments in spring and 10 catchments in autumn, even wet antecedent moisture condition curve numbers based on soil and land use under-predicted the observed flows. This indicated the selection of curve numbers for these two seasons based on soil and land use needs to be revisited. Calculation of curve numbers based on 5-year return period rainfall and flow data indicated that the best-fit curve number from one season grossly over-predicted or under-predicted flows for other seasons for the same catchment. Also, the traditional method of employing catchment-scale, annual curve number irrespective of seasons might not suit the Otago catchments tested, where seasonal rainfall and flow variations are appreciable. Thus, in catchments where the resulting storm flow includes runoff from rainfall and snow melt, calculation of best-fit curve numbers from rainfall and flow alone can result in inaccuracies. Selection of curve number and the effectiveness of the curve number model for flow prediction in Otago catchments may be further enhanced by the inclusion of storm events of other return periods in addition to representation of seasonal flow generation behaviour of the catchments.

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