Chapter 4
Coastal Flood Forecasting Modeling and Analysis

Lei Wang and Xin Zhang

Abstract The mechanism of flood forecasting is a complex process, which involves precipitation, drainage-basin characteristics, land use/cover types, and runoff discharge. Because of the complexity of flood forecasting, hydrological models and statistical models need to be developed for flood frequency analysis, river runoff prediction, and flood forecasting. In this chapter, Soil Conservation Service (SCS) Curve Number (CN) model is applied for river runoff prediction in the Oak Ridges Moraine (ORM) area, southern Ontario. The historical data for the past several decades (river gauging, precipitation, ground water, census and land use) are used to model the relationship among the stream runoff, precipitation and hydrological-geographical features to apply SCS CN model for river runoff prediction.

Keywords Flood forecasting • Model

4.1 US-SCS Curve Number Method

The Soil Conservation Service (SCS) Curve Number (CN) (USDA-SCS 1972) method is widely used for estimating runoff (Viessman and Lewis 2003). The method was originally described in 1954 and been revised in 1956, 1964, 1965, 1971, 1972, 1985 and 1993 (Ponce and Hawkins 1996). The SCS method associates runoff (Q) and precipitation (P) in watershed context with a parameter CN that is influenced by land use type in the drainage basin. The SCS CN method is one of the

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most popular methods for computing runoff volume from a rainstorm, and it is probably one of the most widely used methods in the United States for estimating floods on rural and urban drainage basins (Maidment 1993)

Recent advances in computers and the availability of GIS tools have made a drastic change in hydrological modeling and development with the application of SCS-CN technique (Nageshwar et al. 1992; Arnold et al. 1993). Although the model has its own limitations (Ponce and Hawkins 1996; Choi et al. 2002; Mishra and Singh 2003), it has been widely used in numerous models (Geetha et al. 2008). And it has been approved applicable and effective for estimating direct runoff volume (Hawkins 1993; Steenhuis et al. 1995). Shi et al. (2007) used the SCS model for surface runoff and flood discharge simulation and found the relative error was 5–9 %. Liu and Li (2008) used the SCS model for different flood event runoff volume simulation and found that the relative error between estimated runoff and observed runoff ranged from 6.68 to 23.34 %, which is within the permissible limit.

Maidment (1993) described the derivation of the basic equation for estimating the volume or depth of runoff for accumulated volumes during a storm. This study repeats the derivation process here in order to clearly explain and understand the basic equation of the SCS CN model.

The general form of the relation is well established by both theory and observation. No runoff occurs until rainfall equals an initial abstraction Ia. After allowing for Ia, the depth of runoff Q is the residual after subtracting F, the infiltration or water retained in the drainage basin (excluding Ia) from the rainfall P. The potential retention S is the value that (F + Ia) would reach in a very long storm (Maidment 1993).

If Pe is the effective storm rainfall equal to (P−Ia), the basic assumption in the method is

$$\frac{F}{S} = \frac{Q}{P - I_a} \tag{4.1}$$

where Q — runoff depth (inch)
P — rainfall (inch)
S — water potential retention maximum of watershed (inch)
Ia — initial abstraction of rainfall by soil and vegetation (inch)
F — actual retention

After runoff starts, all excess rainfall becomes either runoff or actual retention. That is

$$F = P - I_a - Q \tag{4.2}$$

Replacing F in Eq. 4.1, then

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \qquad (P > I_a) \qquad Q = 0 \qquad (P \leq I_a) \tag{4.3}$$

The empirical relation Ia = 0.2S was adopted as the best approximation from observed data, so

$$\begin{aligned} Q &= \left[\frac{(P - 0.2S)^2}{(p + 0.8S)}\right] && \text{for } \mathrm{P} > 0.2\mathrm{S} \\ Q &= 0 && \text{for } \mathrm{P} \leq 0.2\mathrm{S} \end{aligned} \tag{4.4}$$

For convenience and to standardize application of this equation, the potential retention S is expressed in the form of a dimensionless runoff Curve Number (CN), where

$$CN = \frac{1000}{S + 10} \tag{4.5}$$

Eliminating S from Eqs. 4.4 and 4.5 gives the basis SCS relationship for estimating Q from P and CN, which has the advantage of having only one parameter.

From Eqs. 4.4 and 4.5, one can calculate CN from given P and Q as follows (Ko 2004):

$$CN = \frac{25400}{S + 254} = \frac{25400}{254 + \frac{(0.4P + 0.8Q) - \sqrt{(0.4P + 0.8Q)^2 - 4 \times 0.04\left(P^2 - PQ\right)}}{2 \times 0.04}} \tag{4.6}$$

The value of CN depends on the soil, cover and hydrological condition of the land surface (Maidment 1993). CN also depends on the antecedent wetness of the drainage basin, and three classes of antecedent moisture condition (AMC) defined: dry, average, and wet (AMC I, AMC II, and AMC III). Selection of the runoff curve number is dependent on antecedent conditions and the types of land cover (Viessman and Lewis 2003).

4.2 Data Preprocessing

Modeling the rainfall-runoff process in the ORM area includes three steps: first, ArcHydro tools use DEM data to delineate the watershed boundary. Then the historical data for the past several decades (river gauging, precipitation, and land cover) are used to model the relationship among the stream runoff, precipitation and hydrological-geographical features to get the CN value for each watershed. Finally, CN value and precipitation are used for river runoff prediction.

4.2.1 Thiessen Polygon to Associate Runoff and Precipitation Stations

In order to model the rainfall-runoff process, stream gauging stations and weather stations need to be associated within the same watershed.

The selected weather stations and the stream gauging stations are mapped using ArcGIS (Fig. 4.1). There are 25 stream gauging stations within the study area, which record daily flow data and 131 weather stations within the study area, which record daily precipitation data.

Since there are more than one weather station located within the same watershed, in order to compare the time series runoff and precipitation, thiessen polygons are applied to associate the weather stations with the stream gauging stations within the same watershed boundary (Fig. 4.2). First, the thiessen polygon method divides the whole space into thiessen polygons by the perpendicular bisectors between those weather stations, and then these thiessen polygons are intersected with the watershed boundary. Finally, the percentage of area of each thiessen polygon within the watershed boundary is used as the weights to calculate the area-weighted average precipitation.

By combining these two layers, each stream gauging station has a pair of time series showing both the stream flow record and the precipitation record covering the same time period.

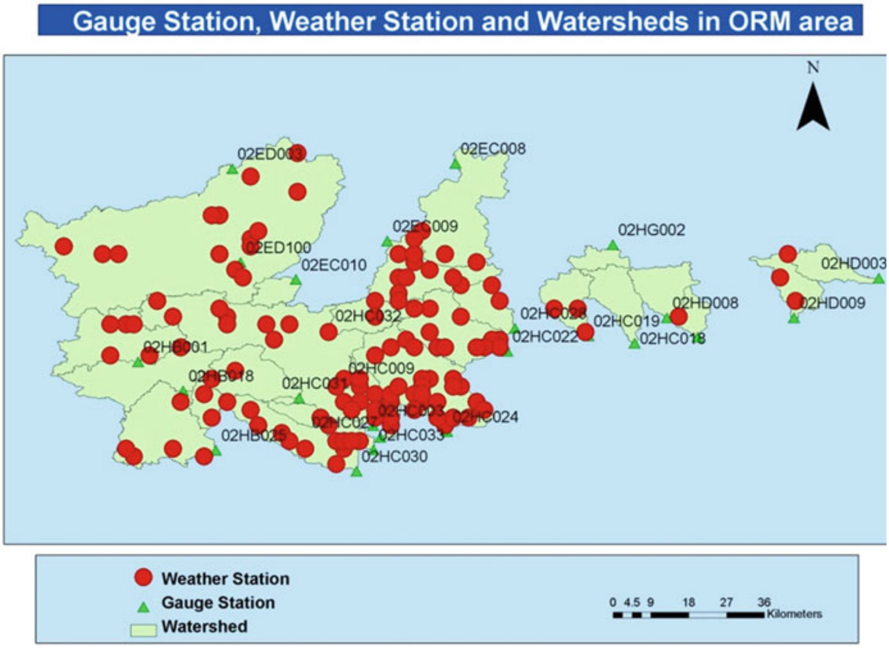


Fig. 4.1 Watersheds, stream gauge stations and precipitation stations in the ORM area

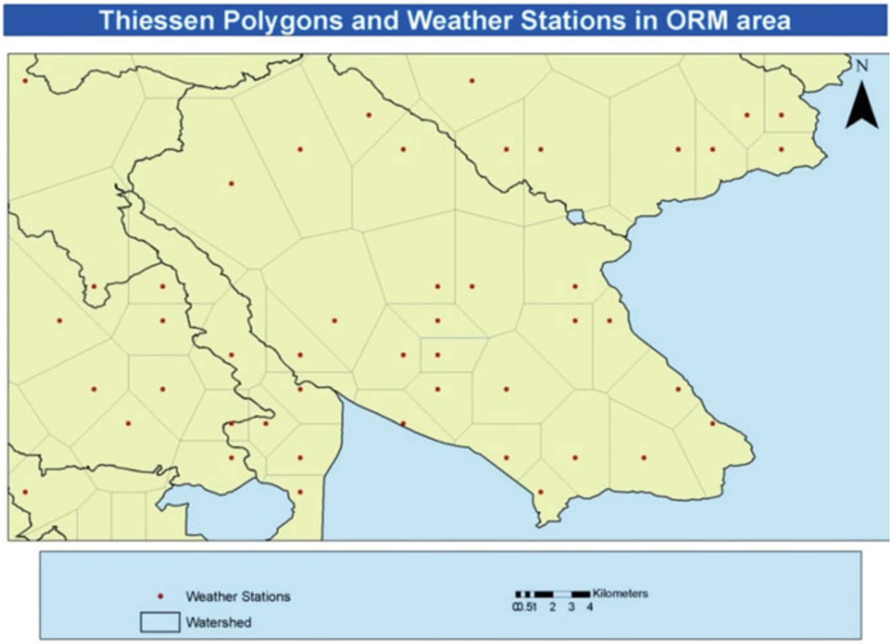


Fig. 4.2 Thiessen polygons and weather stations in the ORM area

The historical data for the past several decades (river gauging, precipitation, and land cover) are used to model the relationship among the stream runoff, precipitation and hydrological-geographical features to obtain the CN value for each watershed. The whole process includes three steps. First, base flow separation, since the SCS model is designed to model the relationship between direct flow and precipitation, so the first step is to study the method to separate base flow from runoff to get direct flow, and therefore each watershed has pairs of rainfall and direct flow depth, and these pairs of rainfall and direct flow depth can be used to calculate pairs of composite CN value. Second, the land cover classification map is interacted with the watershed boundary map to get the land cover percentage in each watershed. Then multiple regression is applied to those pairs of composite CN values and land cover percentage in each watershed to get the CN values for different land covers in the ORM area. Finally, these CN values are used to calculate the composite CN values for each watershed, and these new composite CN values are used for river runoff prediction.

Because the SCS CN method is designed for computing runoff volume from a rainstorm, in order to avoid the mixing of river flow due to rainfall and snow melt, only the flood events that occurred from May 1 to November 30 are used to model the relationship among the stream runoff, precipitation and hydrological-geographical features to apply the SCS CN model for river runoff prediction in the ORM area.

4.2.2 Base Flow Separation

Most of techniques used to separate a total runoff into direct surface runoff and base flow components are based on analysis of groundwater recession curves. A groundwater recession is characterized by a gradually decreasing rate of base flow. The recession curve shape has been found to approximate an exponential function (Viessman and Lewis 2003).

If there is no added inflow to the groundwater, and if all groundwater discharge from the upstream area is intercepted at the stream gauging station, then the groundwater discharge recession can be described by (Viessman and Lewis 2003):

$$Q_t = Q_0 e^{-\theta t} \tag{4.7}$$

where Q_0 — a specified initial discharge
Qt — the discharge at any time t after flow Q0
θ — the recession constant
e — base of the natural logarithm

Time units frequently used are days for large watersheds and hours for small basins.

The May 1974 flood event at the 02HB001 gauging station is used as an example for base flow recession and separation analysis. The May 1974 flood event started on May 14 and reached peak flow on May 17. After that, there was no rainfall until May 27. The river flow discharge and precipitation observed at 02HB001 gauging stations during this flood event are listed in Table 4.1.

We can apply log transform of river flow discharge for the May 1974 flood to study base flow recession (Fig. 4.3). Since the log value of the river flow discharge approximately fitted a straight line from May 20 to May 28, the direct flow was assumed to end on May 20, and the river flow was composed of base flow only from May 20 to May 28. The base flow recession coefficient was 0.088.

Using base flow recession Eq. (4.7), the base flow can be calculated as follows: Since the river flow was composed of base flow only on May 20 (3.74 m^3/s), the base flow for May 19 and May 18 can be calculated inversely by the base flow recession Eq. (4.7), with a recession coefficient of 0.088. Since the flood event started on May 14, the river flow on May 14 was also considered to be composed of base flow only, and the base flow from May 15 to May 17 can be calculated using a linear interpolation method. Then the direct flow can be calculated by separating base flow from runoff, and the direct flow depth can be calculated by dividing the total direct flow amount by the drainage basin area (205 km^2).

The results of base flow separation and direct flow depth obtained for the May 1974 flood event are listed in Table 4.2.

Similarly, pairs of direct flow depth and precipitation of each gauging station can be calculated for different flood events and these pairs of direct flow depth and precipitation are used for multiple regression analysis to get the CN value for different soil types (land covers) in the ORM area.

Table 4.1 River flow discharge and precipitation observed at 02HB001 gauging stations

Date	River flow discharge (m^3/t)	Precipitation (mm)
5-14-1974	2.940	11.2
5-15-1974	3.450	4.1
5-16-1974	4.530	36.3
5-17-1974	15.300	0
5-18-1974	9.120	0
5-19-1974	5.270	0
5-20-1974	3.740	0
5-21-1974	3.170	0
5-22-1974	2.830	1.5
5-23-1974	2.890	0
5-24-1974	2.550	0
5-25-1974	2.240	0
5-26-1974	2.000	0
5-27-1974	1.940	0.6
5-28-1974	1.830	3

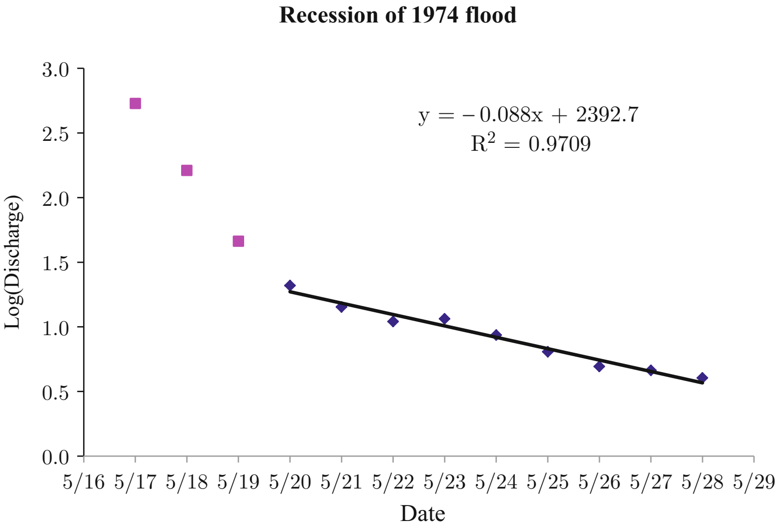


Fig. 4.3 Log transform of hydrograph of May 1974 flood

Table 4.2 Precipitation, direct flow depth for May 1974 flood event at gauging stations in the ORM area

Gauge station	Precipitation (mm)	Flow depth (mm)
02EC008	–	–
02EC009	31.9	8.1
02EC010	32.9	6.2
02ED003	30.5	6.8
02ED100	48.2	6.1
02HB001	53.1	7.6
02HB018	–	–
02HB025	–	–
02HC003	43.7	20
02HC009	33.6	9.3
02HC018	–	–
02HC019	25.4	5.5
02HC022	29.7	6.8
02HC024	41.6	20.3
02HC027	52.4	31.6
02HC028	31.8	13.2
02HC030	67.2	39.2
02HC031	–	–
02HC032	29	5.9
02HC033	60.3	31
02HD003	31.4	7.6
02HD008	36.5	8.8
02HD009	32.9	5.9
02HD013	–	–
02HG002	–	–

4.2.3 Antecedent Moisture Condition (AMC)

As described in Sect. 4.2.3, the Antecedent Moisture Condition (AMC) refers to the wetness of the soil surface or the amount of moisture in the soil (Mishra and Singh 2003). If the soil is fully saturated, the entire amount of rainfall will directly convent to runoff without infiltration losses and if the soil is fully dry, it is possible that there is no surface runoff because the whole rainfall amount is absorbed by the soil. The AMC has significant effect to the process of rainfall runoff (Mishra and Singh 2003).

AMC is based on the amount of antecedent rainfall, and it varies from previous 5 to 30 days. However, there is no explicit guideline available to define the soil moisture using the antecedent rainfall. The National Engineering Handbook (USDA-SCS 1968) uses the antecedent 5-day rainfall for AMC and it is generally used in practice (Mishra and Singh 2003). In this study, the antecedent 5-day rainfall for AMC is used for AMC analysis.

4.3 CN Value

The runoff estimation method used in this study is the SCS model developed by the US Soil Conservation Service. The SCS method associates Runoff (Q) and Precipitation (P) in the watershed context with a parameter CN that is influenced by land use types in the drainage basin. The SCS curve method integrates the contribution of precipitation and soil properties to estimate the storm runoff volume.

The CN values are the empirically derived values for different land types. CN values depend on the surface cover and soil moisture of a particular place. SCS recommend CN value for different antecedent conditions and the types of land cover. The suggested values could be found in National Engineering Handbook (USDA-SCS 1985). However, this recommended value may or may not fit for the ORM area.

4.4 Composite CN Value

Grove et al. (1998) suggested that the average CN for a watershed can be calculated in two ways: the "composite method" and the "distributed method." In the composite method, the CN values for each soil type are identified and the average CN for the watershed can be calculated as the area weighted average CN of each soil type occupying the watershed. Conversely, the distributed method identifies the different land uses and computers the runoff volume for each land use and the total runoff volume is the sum of all runoff volume for each land uses type. In this study, the composite method is used to calculate the average CN.

In this study, the National-Scale Ontario Land Cover Map (Ontario Ministry of Natural Resources 1999) was used to calculate the area weighted average CN of each watershed. This may have some impact to model simulation because the 1999 land cover may not represent the actual types of land cover when different flood events happened. However, because of data limitation, there are no other land cover maps available, so the National-Scale Ontario Land Cover Map is used as land cover map in this study. Figure 4.4 shows the land cover map, which shows a total of six land cover classes: water, forest, wetlands, agriculture, bare soil, and urban.

Geoprocessing (such as intersect) is then applied to get the area percentage of different land cover classes at each watershed. Table 4.3 shows the area percentage of different land cover classes at each watershed.

A composite curve number (CN) for a watershed having more than one land use or soil type can be obtained by weighting each curve number based on its area percentage. Although there are six land cover classes at the National-Scale Ontario Land Cover Map, the area percentage of water body, grass land and bare soil are

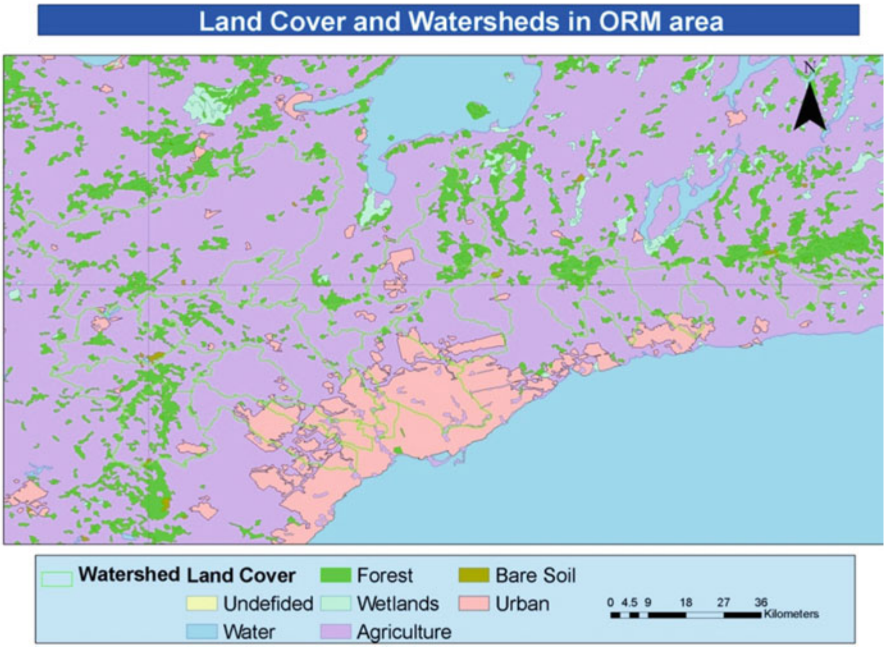


Fig. 4.4 Land cover and watersheds in the ORM area

very small for the study area watershed, so the composite CN for each watershed in the ORM area can be calculated as:

$$\begin{aligned}\text{Composite CN} = {} & \%\,\text{area of forest} * \text{CN forest} + \%\,\text{area of agriculture} * \\ & \text{CN agriculture} + \%\,\text{area of urban} * \text{CN urban}\end{aligned} \tag{4.8}$$

The SCS recommended CN value for different antecedent conditions, and the types of land cover from the National Engineering Handbook (USDA-SCS 1985) might need to be adjusted to fit the ORM area. The CN values involved in the model are determined by using multiple regression method.

The whole process includes three steps: first, pairs of direct flow and precipitation of each watershed can be calculated for different flood events and these pairs of direct flow and precipitation can be used to calculate the composite CN values for different flood events and watersheds using Eq. (4.6). Then these pairs of calculated composite CN values are classified into three classes: AMC I, AMC II, AMC III. Among them AMC II is used as case study to illustrate the CN values calculation process for different land cover type. Finally, multiple regression is applied to get the CN values for different land cover types including agriculture, forest and urban.

Table 4.4 lists the selected flood events in southern or central Ontario from May to November. However, not all flood events have enough rainfall-runoff data

Table 4.3 Area percentage of different land cover classes at each watershed in the ORM area

Watershed	Water body	Forest	Grass land	Agriculture	Bare soil	Urban
02EC008		25.93	2.55	71.20		0.32
02EC009		14.29		69.60	2.55	13.56
02EC010		1.86		98.14		0.00
02ED003		4.66		95.17		0.18
02ED100		3.15		96.85		0.00
02HB001	0.68	13.27		80.81	5.23	0.00
02HB018		20.81		78.05	0.33	0.80
02HB025		25.00		71.75		3.25
02HC003		0.00		53.33		46.67
02HC009		1.64		90.17		8.18
02HC018		4.69		85.88		9.43
02HC019		24.95		75.05		0.00
02HC022		1.64		75.07		23.29
02HC024		0.00		8.47		91.53
02HC027		0.58		21.23		78.19
02HC028		0.00		99.43		0.57
02HC030		0.00		29.16		70.84
02HC031		0.37		96.53		3.09
02HC032	0.51	4.68		87.47		7.35
02HC033		0.00		25.13		74.87
02HD003		45.72		54.28		0.00
02HD008		2.27		96.83		0.90
02HD009		14.61		85.39		0.00
02HD013		3.06		60.75		36.18
02HG002		37.03		62.97		0.00

Table 4.4 Selected flood events in southern or central Ontario from May to November

Rec	Year	Month	Day
1	1954	10	15
2	1956	08	30
3	1960	05	09
4	1974	05	17
5	1979	05	12
6	1992	07	31
7	1992	08	28
8	2002	05	13

Source: Canadian Disaster Database

available for modeling analysis. For example, for 1954, 1956 and 1960 flood events, only 5 gauging stations have rainfall-runoff data available; for May 1979 and July 1992 flood events, only 12 gauging stations have rainfall-runoff data available. So May 1974, Aug. 1992 and May 2002 flood events are selected to

Table 4.5 Composite CN and AMC types for May 2002 flood event

Watershed	Composite CN	Total 5-day antecedent rainfall (mm)	AMC type
02EC008	–	–	–
02EC009	69.5	5.6	AMCI
02EC010	66.33	17	AMCII
02ED003	83.47	29	AMCIII
02ED100	65.79	13.9	AMCII
02HB001	66.81	28.1	AMCIII
02HB018	68.35	22	AMCII
02HB025	67.72	19	AMCII
02HC003	77.04	22	AMCII
02HC009	71.09	26	AMCII
02HC018	70.57	15.6	AMCII
02HC019	67.62	14.9	AMCII
02HC022	84.94	15	AMCII
02HC024	81.45	19.2	AMCII
02HC027	81.67	17.7	AMCII
02HC028	83.49	23.8	AMCII
02HC030	84.33	17	AMCII
02HC031	81.12	22	AMCII
02HC032	–	–	–
02HC033	88.71	18	AMCII
02HD003	59.08	14	AMCII
02HD008	66.51	15.3	AMCII
02HD009	54.92	14.2	AMCII
02HD013	80.7	14	AMCII
02HG002	–	–	–

illustrate modeling process, these three flood events have 18, 21 and 22 gauging stations having rainfall-runoff data available for modeling analysis. May 2002 flood event is selected to apply multiple regression to get the CN values for different land cover types because the land cover map is developed in 1999, and May 1974 and Aug. 1992 flood events are used to verify the suitability of the CN values.

Table 4.5 is the composite CN values and AMC types for May 2002 flood event. Among them, those composite CN values that belong to AMC II type are selected for multiple regression analysis.

Since composite CN values can be consider as the area weighted average of CN values, so composite CN values can be expressed as a linear combination of land cover types and area percentage as Eq. (4.8). Using these paired composite CN values for different flood events and watersheds, the multiple regression can be applied to get the CN values for different land cover types including agriculture, forest and urban. Table 4.6 shows the results of multiple regression CN values.

Table 4.6 Results of multiple regression CN values

	Unstandardized coefficients		Standardized coefficients	
	B	Std. error	Beta	t
Forest	40.569	11.796	0.080	3.439
Agriculture	72.814	2.411	0.726	30.197
Urban	87.564	3.892	0.463	22.501

Table 4.7 Results of multiple regression CN values (second times)

	Unstandardized coefficients		Standardized coefficients	
	B	Std. error	Beta	t
Agriculture	69.628	2.339	0.736	29.773
Urban	88.818	4.412	0.498	20.130

For the multiple regression, R2 is 0.994 and the CN values of forest, agriculture and urban for AMC II are 41, 73 and 88 separately. The corresponding CN values for AMC I and AMC III can be obtained from "CN for Wet and Dry Antecedent Moisture Conditions Corresponding to an Average Antecedent Moisture Conditions" Table from (Viessman and Lewis 2003).

However, when apply these CN values for flood simulation, the relative error is still relatively large (the average relative error is near 26 % for May 1974 flood event and near 45 % for August 1992 flood event), and further investigation found that the CN value for forest is smaller than the recommended value (70) from SCS, this might because the area percentage of forest is small in most watersheds, which cause the contribution of forest for the regression to be relatively small. Thus the multiple regression needs to be re-applied again to modify the CN values for different land cover types. This time the recommended CN value for forest was not included in the multiple regression, only the CN values for agriculture and urban were included in the regression analysis. Table 4.7 shows the results of multiple regression CN values.

For the multiple regression, R2 is 0.990 and the CN values of forest, agriculture and urban for AMC II are 70, 70 and 89 separately.

Based on above two multiple regressions, the CN values of agriculture, forest and urban for AMC II were determined to be 70, 70 and 89 separately. The corresponding CN values for AMC I and AMC III can be obtained from "CN for Wet and Dry Antecedent Moisture Conditions Corresponding to an Average Antecedent Moisture Conditions Table" from (Viessman and Lewis 2003).

Table 4.8 shows the area percentage of different land cover clases and corresponding CN value for different Antecedent Moisture Condition (AMC).

After weighted area calculation, the composite CN value at each watershed is listed in Table 4.9.

Table 4.8 CN value for each watershed in the ORM area

Watersheds	Land use	Area percentage (%)	AMC I	AMC II	AMC III
02ec008	Forest	25.93	51	70	85
	Agriculture	71.20	51	70	85
	Urban	0.32	76	90	96
02ec009	Forest	14.29	51	70	85
	Agriculture	69.60	51	70	85
	Urban	13.56	76	90	96
02ec010	Forest	1.86	51	70	85
	Agriculture	98.14	51	70	85
	Urban		76	90	96
02ed003	Forest	4.66	51	70	85
	Agriculture	95.17	51	70	85
	Urban	0.18	76	90	96
02ed100	Forest	3.15	51	70	85
	Agriculture	96.85	51	70	85
	Urban		76	90	96
02hb001	Forest	13.27	51	70	85
	Agriculture	80.81	51	70	85
	Urban		76	90	96
02hb018	Forest	20.81	51	70	85
	Agriculture	78.05	51	70	85
	Urban	0.80	76	90	96
02hb025	Forest	25.00	51	70	85
	Agriculture	71.75	51	70	85
	Urban	3.25	76	90	96
02hc003	Forest		51	70	85
	Agriculture	53.33	51	70	85
	Urban	46.67	76	90	96
02hc009	Forest	1.64	51	70	85
	Agriculture	90.17	51	70	85
	Urban	8.18	76	90	96
02hc018	Forest	4.69	51	70	85
	Agriculture	85.88	51	70	85
	Urban	9.43	76	90	96
02hc019	Forest	24.95	51	70	85
	Agriculture	75.05	51	70	85
	Urban		76	90	96
02hc022	Forest	1.64	51	70	85
	Agriculture	75.07	51	70	85
	Urban	23.29	76	90	96

(continued)

Table 4.8 (continued)

Watersheds	Land use	Area percentage (%)	AMC I	AMC II	AMC III
02hc024	Forest		51	70	85
	Agriculture	8.47	51	70	85
	Urban	91.53	76	90	96
02hc027	Forest	0.58	51	70	85
	Agriculture	21.23	51	70	85
	Urban	78.19	76	90	96
02hc028	Forest		51	70	85
	Agriculture	99.43	51	70	85
	Urban	0.57	76	90	96
02hc030	Forest		51	70	85
	Agriculture	29.16	51	70	85
	Urban	70.84	76	90	96
02hc031	Forest	0.37	51	70	85
	Agriculture	96.53	51	70	85
	Urban	3.09	76	90	96
02hc032	Forest	4.68	51	70	85
	Agriculture	87.47	51	70	85
	Urban	7.35	76	90	96
02hc033	Forest		51	70	85
	Agriculture	25.13	51	70	85
	Urban	74.87	76	90	96
02hd003	Forest	45.72	51	70	85
	Agriculture	54.28	51	70	85
	Urban		76	90	96
02hd008	Forest	2.27	51	70	85
	Agriculture	96.83	51	70	85
	Urban	0.90	76	90	96
02hd009	Forest	14.61	51	70	85
	Agriculture	85.39	51	70	85
	Urban		76	90	96
02hd013	Forest	3.06	51	70	85
	Agriculture	60.75	51	70	85
	Urban	36.18	76	90	96
02hg002	Forest	37.03	51	70	85
	Agriculture	62.97	51	70	85
	Urban		76	90	96

Table 4.9 Composite CN value at each watershed in the ORM area

Watersheds	AMC I	AMC II	AMC III
02EC008	51	70	85
02EC009	55	73	86
02EC010	51	70	85
02ED003	51	70	85
02ED100	51	70	85
02HB001	52	70	85
02HB018	51	70	85
02HB025	52	71	85
02HC003	64	79	90
02HC009	53	72	86
02HC018	54	72	86
02HC019	51	70	85
02HC022	57	75	88
02HC024	76	88	95
02HC027	72	86	94
02HC028	51	70	85
02HC030	70	84	93
02HC031	52	71	85
02HC032	53	72	86
02HC033	71	85	93
02HD003	51	70	85
02HD008	51	70	85
02HD009	51	70	85
02HD013	61	77	89
02HG002	51	70	85

4.5 Runoff Simulation Using SCS CN Model in the ORM Area

The May 1954 and August 1992 flood events are simulated using the SCS CN model, and the results are shown in Tables 4.10 and 4.11 separately. Generally, it shows an average of 70 % accuracy for the flood simulation and 30 % of relative error (the average relative error is 17 % for May 1974 flood event and near 37 % for 1992 flood event). The reasons for the relative error may include: First, the accuracy of land cover map, it is a National Scale Land Cover Map of 1999 derived from a more detailed Provincial-Scale Ontario Land Cover data base by combining and redefining the original 28 classes to form 15 classes and by generalizing the original spatial resolution from 25 to 100 meters. Discrete features less than 50 hectares in size were eliminated, and the Ontario land cover classification reflects the nature of the land surface rather than the land use (Ontario Ministry of Natural Resources 1999). This land cover map may not represent the actual types of land cover. Second, some watersheds have a large area, however, the SCS CN model is

Table 4.10 Runoff simulation results for May 1974 flood in the ORM area

Watersheds	Event precipitation (mm)	AMC type	Calculated direct flow (mm)	Measured direct flow (Mm)	Relative error (%)
02EC008	–	–	–	–	–
02EC009	31.9	AMCIII	9	8.1	11.4
02EC010	32.9	AMCIII	8.3	6.2	35.5
02ED003	30.5	AMCIII	7	6.8	3.4
02ED100	48.2	AMCII	5.2	6.1	−15.4
02HB001	53.1	AMCII	7	7.6	−8.4
02HB018	–	–	–	–	–
02HB025	–	–	–	–	–
02HC003	43.7	AMCIII	22.1	20	10.3
02HC009	33.6	AMCIII	9.6	9.3	2.9
02HC018	–	–	–	–	–
02HC019	25.4	AMCIII	4.4	5.5	−19.8
02HC022	29.7	AMCIII	8.6	6.8	26.9
02HC024	41.6	AMCII	17.8	20.3	−12.6
02HC027	52.4	AMCIII	36.1	31.6	16.3
02HC028	31.8	AMCIII	7.8	13.2	−41
02HC030	67.2	AMCIII	48.2	39.2	23.1
02HC031	–	–	–	–	–
02HC032	29	AMCIII	6.8	5.9	16.8
02HC033	60.3	AMCII	30.5	31	−1.4
02HD003	31.4	AMCIII	7.5	7.6	−1.4
02HD008	36.5	AMCIII	10.6	8.8	20.1
02HD009	32.9	AMCIII	8.3	5.9	41.2
02HD013	–	–	–	–	–
02HG002	–	–	–	–	–

designed for small-area watersheds, which have a relatively simple land cover type. The large-area watersheds may not fit for the SCS model for rainfall-runoff modeling. These watersheds need to be separated into several small watersheds for SCS modeling analysis.

Similarly, the simulation results for August 1992 flood event are shown in Table 4.11.

4.6 Water Level Prediction

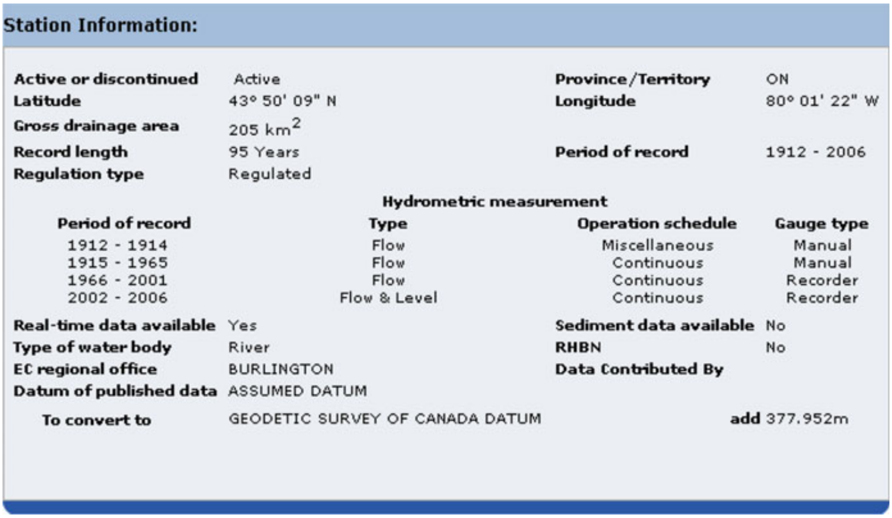
Water level is important for flood forecasting. Water Survey Canada (WSC) measures the water level (called stage) and uses a "Stage–Discharge Curves" (rating curve) to translate the stage into discharge for each gauging station. For

Table 4.11 Runoff simulation results for August 1992 flood in the ORM area

Watersheds	Event precipitation (mm)	AMC type	Calculated direct flow (mm)	Measured direct flow (mm)	Relative error (%)
02EC008	80.7	AMCI	3.8	2.6	−42.8
02EC009	64.1	AMCII	14.3	20.0	−28.4
02EC010	–	–	–	–	–
02ED003	47.3	AMCI	0.3	1.5	−78.4
02ED100	–	–	–		
02HB001	69.7	AMCI	0.8	3.8	−78.5
02HB018	69	AMCI	1.6	5.7	−71.5
02HB025	68.4	AMCII	1.8	4.0	−55.9
02HC003	61.6	AMCII	20.4	20	2.2
02HC009	65.4	AMCII	14.1	8.6	63.5
02HC018	67	AMCII	2.2	5.4	−60
02HC019	69.2	AMCII	14.4	8.6	67.4
02HC022	–	–	–	–	–
02HC024	63.5	AMCI	17.3	18.0	−3.8
02HC027	67.7	AMCII	34.4	29.3	17.4
02HC028	67.1	AMCII	13.4	16.9	−20.5
02HC030	65.7	AMCI	12.8	20.8	−38.7
02HC031	58.8	AMCII	9.9	13.1	−24.4
02HC032	51.9	AMCII	7.6	6.1	24.9
02HC033	66.2	AMCII	32.1	30.5	−5.1
02HD003	75.5	AMCI	3.3	5.3	−37.3
02HD008	65.5	AMCI	1.1	2.1	−46.8
02HD009	80	AMCI	4.2	3.3	28
02HD013	65.9	AMCI	5.6	6.8	−18.2
02HG002	–	–	–	–	–

flood forecasting purposes, the rating curve can also be used to translate the runoff prediction to water level prediction.

WSC supplies both water level and discharge data from 2002 to 2006 (Fig. 4.5). Before 2002, only flow discharge data was available, not water level data. The flow discharge and water level data from 2002 to 2006 can be used to model the relationship between water level and discharge to get a water level (stage) discharge curve, and this curve can be used to calculate the discharge from the water level or calculate water level from the discharge.



Station Information:

Active or discontinued	Active	**Province/Territory**	ON
Latitude	43° 50' 09" N	**Longitude**	80° 01' 22" W
Gross drainage area	205 km^2		
Record length	95 Years	**Period of record**	1912 - 2006
Regulation type	Regulated		

Hydrometric measurement

Period of record	**Type**	**Operation schedule**	**Gauge type**
1912 - 1914	Flow	Miscellaneous	Manual
1915 - 1965	Flow	Continuous	Manual
1966 - 2001	Flow	Continuous	Recorder
2002 - 2006	Flow & Level	Continuous	Recorder

Real-time data available	Yes	**Sediment data available**	No
Type of water body	River	**RHBN**	No
EC regional office	BURLINGTON	**Data Contributed By**	
Datum of published data	ASSUMED DATUM		
To convert to	GEODETIC SURVEY OF CANADA DATUM	**add**	377.952m

Fig. 4.5 Station information of O2HB001 gauging station (Environment Canada)

4.6.1 Stage Discharge Relation

"Stage-discharge relationship" is the relation between the water level (stage) and the discharge at a gauging station. Discharges in rivers are typically estimated by combining water level records with a functional relation, or suite of relations, describing variations in measured discharges with changing water levels. The functional relation between water level (or stage) and discharge is known as a stage-discharge curve, or rating curve (DeGagne et al. 1996). A series of national and international standards (ISO, 1981, 1982, 1983) have established procedures for measuring stage and discharge, as well as the development of stage-discharge relations.

A thorough understanding of the relationship between river stage and discharge is essential because one of the basic responsibilities of a hydrometric technician is to collect and compute daily discharge data for publication purposes. A stage-discharge relationship needs to be supported by real data. The more data points used to develop a graph, the better. Periodic checks of the discharge curve should be made after periods of flooding. The curve should be recalibrated if the periodic checks indicate the relationship has changed. Eventually, natural changes in the stream bottom will result in a change in the relationship between flow and gage height (Environment Canada 1999).

4.6.2 Stage–Discharge Curves

Stream gauging stations are used to measure the height (stage) and discharge in a stream. After a sufficient period of record, a rating curve can be derived, and subsequent discharge estimated given the river's stage.

Normally, a statistically based modeling method is used to model Stage–Discharge Curves. A major advantage of using statistically based modeling over conventional graphical methods of curve fitting is the ability to specify levels of accuracy to the curves, and the discharge estimate. A linear regression analysis is the modeling technique used to create the stage discharge relationship (DeGagne et al. 1996).

The stage-discharge relation may be expressed by an equation of the form (Herschy 1985):

$$Q = K(H + a)\ n \tag{4.9}$$

which is the equation of parabola where Q is the discharge in cubic meters per second

K is a constant
H is the gauge height
"a" is the gauge height at which discharge is zero

And n is an exponent.

Equation (4.9) can be transformed by logarithms to:

$$\mathrm{Log}\ Q = \log K + n \log(H + a) \tag{4.10}$$

which is equivalent to the equation of a straight line $y = mx + c$, where $y = \log Q$, $c = \log K$ and $x = \log\ (H + a)$. Since "a" cannot be measured accurately, it must be determined by various numerical methods. With "a" determined, least squares regression is used to estimate K and n.

Plotting Q against H on log-log paper when "a" is not zero will produce a curve. If the value of "a" is known, Q can be plotted against (H + a) and obtain a straight line result. So in order to get "a," various values of "a" are assumed until values of Q against (H + a) gives a straight line on log-log paper.

When a quantity has to be added to the gauge heights in order to obtain a straight line, "a" is taken as positive, that means, the zero of the gauge is positioned at a level above the point of zero heights. Conversely, when a quantity has to be subtracted from the gauge heights, "a" is taken as negative and, that means the zero of the gauge is positioned at a level below the point of zero heights (Herschy 1985).

In order to get the Stage–Discharge Curves for each basin, the discharge and water level data (2002–2005) are extracted for each gauging station, these measurements are plotted on a long-log paper, and then various values of "a" are

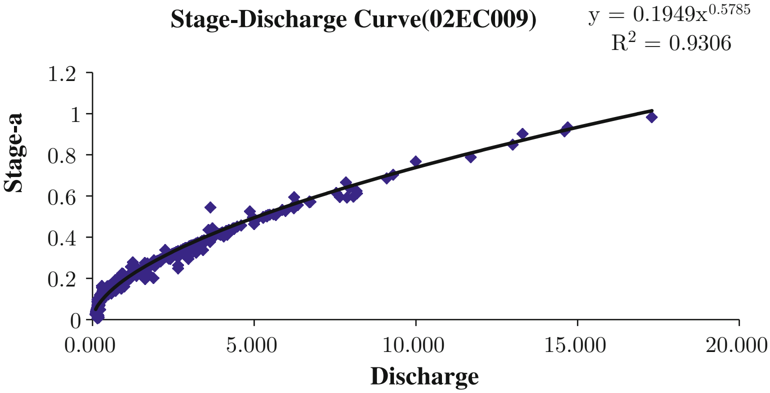


Fig. 4.6 Stage-discharge curve at O2EC009 station

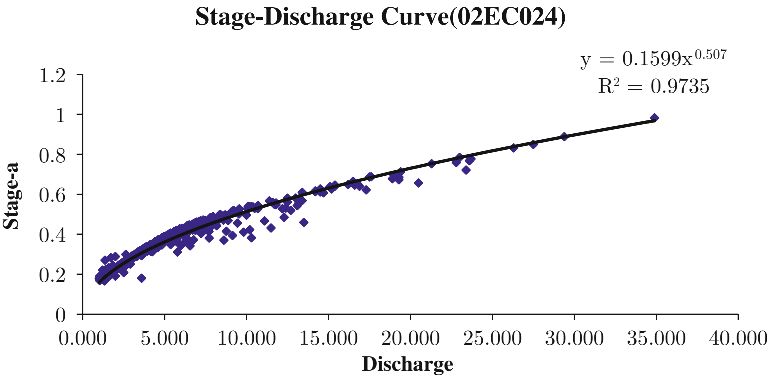


Fig. 4.7 Stage-discharge curve at 02HC024 station

assumed until values of Q against (H + a) give a straight line on log-log paper to determine the best fitting curve to model the Stage–Discharge relationship.

Figures 4.6 and 4.7 show the Stage-Discharge curves at 02EC009 and 02HC024 gauging stations by using the multi-regression method. Using Stage–Discharge Curves, the discharge can be interpolated on the Stage–Discharge Curves for water level prediction.

Rating curve need to be extrapolated when a water level is recorded below the lowest or above the highest gauged level (Maidment 1993). Table 4.12 shows the extrapolation of current rating curves used by WSC at 02EC008 station. And Figs. 4.8 and 4.9 show the extrapolation of the rating curve at 02ED008 and 02EC009 stations separately.

Table 4.12 Working table of current rating curves for 02EC008 station

Gauge height (m)	Discharge (m^3/s)	Gauge height (m)	Discharge (m^3/s)	Gauge height (m)	Discharge (m^3/s)	Gauge height (m)	Discharge (m^3/s)
8.1	0	8.25	0.484	8.5	1.7	9.6	11.2
8.11	0.022	8.26	0.522	8.55	1.98	9.7	12.4
8.12	0.048	8.27	0.561	8.6	2.28	9.8	13.6
8.13	0.075	8.28	0.6	8.65	2.58	9.9	14.8
8.14	0.103	8.29	0.64	8.7	2.89	10	16.1
8.15	0.132	8.3	0.682	8.75	3.2	10.1	17.4
8.16	0.163	8.32	0.77	8.8	3.52	10.2	18.8
8.17	0.196	8.34	0.862	8.85	3.85	10.3	20.3
8.18	0.23	8.36	0.96	8.9	4.2	10.4	21.9
8.19	0.265	8.38	1.06	8.95	4.58	10.5	23.5
8.2	0.3	8.4	1.16	9	4.99	10.6	25.2
8.21	0.336	8.42	1.26	9.1	5.85	10.7	26.9
8.22	0.372	8.44	1.37	9.2	6.82	10.8	28.7
8.23	0.409	8.46	1.48	9.3	7.8	10.9	30.6
8.24	0.446	8.48	1.59	9.5	10	11	32.7

Source: WSC

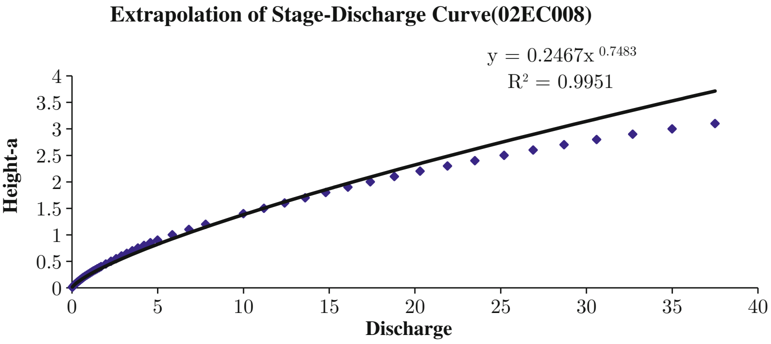


Fig. 4.8 Extrapolation of stage-discharge curve at 02EC008 station

4.7 Summary

The historical data for the past several decades (river gauging, precipitation, ground water, census and land use) are used to model the relationship among the stream runoff, precipitation and hydrological-geographical features to develop a hydrological model for river runoff prediction. The whole process includes three steps. First, base flow separation, since the SCS model is designed to model the relationship between direct flow and precipitation, so the first step is to study the method to

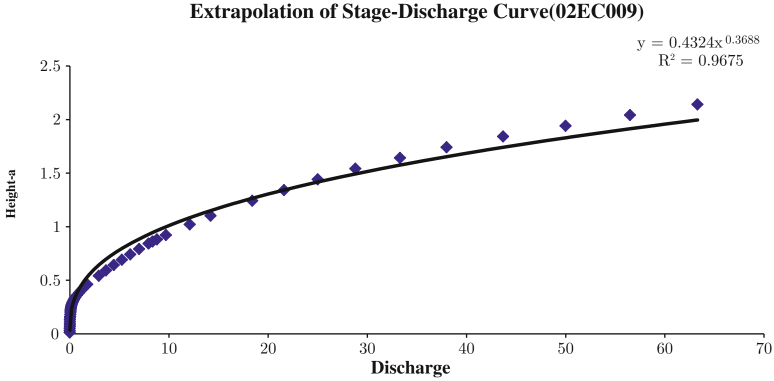


Fig. 4.9 Extrapolation of stage-discharge curve at 02EC009 station

separate base flow from runoff to get direct flow, and therefore each watershed has pairs of rainfall and direct flow depth, and these pairs of rainfall and direct flow depth can be used to calculate pairs of composite CN value. Second, the land cover classification map is interacted with the watershed boundary map to get the land cover percentage in each watershed. Then multiple regression is applied to those pairs of composite CN values and land cover percentage in each watershed to get the CN values for different land covers in the ORM area. Finally, these CN values are used to calculate the composite CN values for each watershed, and these new composite CN values are used for river runoff prediction.

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