CHAPTER 11

# Determination of peak runoff rate

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### Summary

Determine the peak runoff rate of a small watershed using the Modified Rational Formula method, and the SCS Dimensionless Unit Hydrograph for an excess rainfall of 1 cm.

### Getting started

The data for this case study are stored on the ILWIS 2.1 CD-ROM in the directory d:\appguide\chap11. If you have already installed the data on your hard-disk, you should start up ILWIS and change to the subdirectory where the data files for this chapter are stored, c:\ilwis21\data\appguide\chap11. If you did not install the data for this case study yet, please run the ILWIS installation program (see ILWIS Installation Guide).

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- Double-click the ILWIS program icon in the ILWIS program group.
- Change the working drive and the working directory until you are in the directory c:\ilwis21\data\appguide\chap11.

Now you are ready to start the exercises of this case study.

## 11.1 Determination of peak runoff rate using the Modified Rational Formula

One important empirical formula for determining the peak rate of runoff is the Rational Formula. This approach was introduced more than 100 years ago. Since then it has become the most widely used method for designing drainage facilities for small urban and rural watersheds. It is characterized by (1) consideration of the entire drainage area as a single unit, (2) estimation of flow at only the most downstream point, and (3) the assumption that rainfall is uniformly distributed over the drainage area.

The rational method is described by the formula 11.1.

$$Q_p = 0.28 * C * I * A \qquad [11.1]$$

where,

$Q_p$ = Peak runoff rate [$m^3$/sec].

C = Runoff coefficient.

I = Rainfall intensity [mm/hr].

A = Drainage area [$km^2$].

In the modified version of the rational formula, a storage coefficient, $C_s$, is included to account for a recession time > the time the hydrograph takes to rise. In the original formula the recession time was assumed to be equal to the time of rise.

The modified rational method is then described by the formula 11.2.

$$Q_p = 0.28 * C_s x C * I * A \qquad [11.2]$$

The rational method follows the assumptions that (1) the predicted peak discharge has the same probability of occurrence (return period) as the used rainfall intensity and (2) the runoff coefficient is constant during the rain storm.

A rainfall with a steady uniform intensity applied to the catchment will cause runoff that will reach its maximum rate when all parts of the watershed are contributing to the outflow. This will happen after the elapsed time $t_c$, the time of concentration. At this time the runoff rate equals the excess rainfall rate.

There are a few well defined criteria for selection of formulas or methods for determining the time of concentration. Therefore the suggestion to (1) check in the literature the origin (region, climate, etc.) and the watershed scale from which the formula was derived, and (2) test more than one formula and critically evaluate the possible differences.

A number of formulas and methods for determining $t_c$ exist. Only one of them will be presented here:

*Kirpich (Ramser) time of concentration equation*. Formula 11.3

$$t_c = 0.0195 * L^{0.77} * S^{-0.385} \qquad (\textit{Kirpich/Ramser}) \qquad [11.3]$$

where,

$t_c$ = Time of concentration [min].

L = Length of main river [m].

S = Distance weighted channel slope [m/m].

### Available data

The materials used in this exercise are:

- Contour and drainage map of the catchment.
- Land use map.
- Soil map with soil attribute table.
- Two tables (Table 11.1 and Table 11.2) with typical C coefficients. Reference is made to the hydrology text books (Schwab *et al.*, 1993).

Table 11.1: Runoff coefficient C for agricultural watersheds (Soil group B)

| Crop and hydrologic condition | Coefficient C for rainfall rates of 25 mm/h | 100 mm/h | 200 mm/h |
|---|---|---|---|
| Row crop, poor practice | 0.63 | 0.65 | 0.66 |
| Row crop, good practice | 0.47 | 0.56 | 0.62 |
| Small grain, poor practice | 0.38 | 0.38 | 0.38 |
| Small grain, good practice | 0.18 | 0.21 | 0.22 |
| Meadow, rotation, good | 0.29 | 0.36 | 0.39 |
| Pasture, permanent, good | 0.02 | 0.17 | 0.23 |
| Woodland, mature, good | 0.02 | 0.10 | 0.15 |

Table 11.2: Hydrologic soil group conversion factors

| Crop and hydrologic condition | Factors for converting the runoff coefficient C from Group B soils to Group A | Group C | Group D |
|---|---|---|---|
| Row crop, poor practice | 0.89 | 1.09 | 1.12 |
| Row crop, good practice | 0.86 | 1.09 | 1.14 |
| Small grain, poor practice | 0.86 | 1.11 | 1.16 |
| Small grain, good practice | 0.84 | 1.11 | 1.16 |
| Meadow, rotation, good | 0.81 | 1.13 | 1.18 |
| Pasture, permanent, good | 0.64 | 1.21 | 1.31 |
| Woodland, mature, good | 0.45 | 1.27 | 1.40 |

### Determine time of concentration

In order to determine the time of concentration, the catchment area, for which the peak runoff rate is going to be determined, has to be inspected on size, land cover and topography.

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- Study the catchment area and determine the size of the total catchment area.
- Study the topography of the catchment area and determine the limits

of the slopes to be encountered.

- Study the land use map.
- Calculate the time of concentration using the formula of Kirpich/Ramser.

### Determine the area weighted runoff coefficient

The rational formula uses C, the runoff coefficient. This coefficient is related to the different land covers and hydrologic soil groups. Within the catchment, more than one land cover type and soil group exist. In order to find a representative runoff coefficient, an overall catchment runoff coefficient has to be determined using the areas of the different land cover/hydrologic soil group complexes as weighing factor.

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- Reclassify the soils map into a map showing the Hydrologic Soil Groups.
- Determine the Land cover/Hydrologic soils group complexes and determine the areas occupied by the different complexes.
- Calculate the different areas for the different land cover/ Hydrologic soil group complexes.
- Determine a runoff coefficient for each complex assuming a rainfall rate of 100 mm/h.
- Calculate the overall catchment runoff coefficient.

### Determine the 10-year return period peak runoff rate

When determining the peak runoff rate according to the rational formula a rainfall intensity, with a certain return period, has to be selected. The duration of the storm has to equal the time of the concentration of the catchment. In this exercise a rainfall intensity of 100 mm/h with a return period of 10 years is used.

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- Calculate the 10-year return period peak runoff rate, assuming a storage coefficient $C_s$ of 0.75.

## 11.2 Determination of peak runoff rate using the SCS Dimensionless Unit Hydrograph

One important empirical formula for determining the quantity of runoff is the SCS Dimensionless Unit Hydrograph (U.S. Soil Conservation Service, 1964). It belongs to the group of isochronal methods for determining peak runoff rates. The method is based on the theory of Sherman (1932). The analysis of a large number of unit hydrographs from catchments of a wide range in size and from different locations led to the formulation of the SCS dimensionless unit hydrograph. In order to use this method the time to peak $t_{peak}$ and the peak discharge $q_{peak}$ are estimated. The method assumes that (1) the duration of excess rainfall, D, is less or equal to 0.133 x the time of concentration $t_c$ and (2) the rainfall duration is not too long ($D<0.2\ t_{peak}$). If these conditions are met the formulas 11.4, 11.5 and 11.6 can be used.

$$t_{peak} = \frac{D}{2} + t_{lag} \qquad [11.4]$$

where,

$t_{peak}$ = Time to peak [hr].

D = Duration of excess rainfall [hr].

$t_{lag}$ = The lag time of the watershed [hr].

and,

$$t_{lag} = 0.6\ t_c \qquad [11.5]$$

where,

$t_c$ = Time of concentration [hr].

The peak runoff rate can be calculated using the formula 11.6.

$$q_{peak} = 2.08\ \frac{RO\ A}{t_{peak}} \qquad [11.6]$$

where,

$q_{peak}$ = Peak runoff rate [m$^3$/s].

RO = Storm runoff or excess rainfall volume [cm].

A = Watershed area [km$^2$].

$t_{peak}$ = Time to peak [hr].

The lag time can be calculated using formula 11.7, proposed by the SCS for estimating lag times of runoff for agricultural, forest and range lands watersheds.

$$t_{lag} = \frac{2.587 * L^{0.8} \left( \frac{1000}{CN} - 9 \right)^{0.7}}{1900 * H^{0.5}} \qquad [11.7]$$

where,

$t_{lag}$ = Lag time [hr].

L = Hydraulic watershed length [m].

CN = Hydrologic area-weighted curve number.

H = Average watershed land slope [%].

The hydraulic watershed length L can be approximated for small watersheds (<2000 ha) by the formula 11.8.

$$L = 110\ A^{0.6} \qquad [11.8]$$

where,

A = watershed area [ha].

The curve numbers CN can be derived from tables that provide SCS Curve Numbers for various soils/land cover complexes. The Curve Numbers can be adjusted by correcting them for antecedent moisture conditions. For the curve number tables, reference is made to the hydrology text books.

## Available data

The materials used in this exercise are:

- Land use map.
- Soil map with soil attribute table.
- A table (Table 11.3) with typical curve numbers. Reference is made to the hydrology text books (Schwab *et al.*, 1993).

Table 11.3: Runoff curve number for hydrologic soil-cover complexes for antecedent rainfall condition II and $I_a$=2S

| Land use or crop | Treatment or practice | Hydrologic condition | Hydrologic soil group A | B | C | D |
|---|---|---|---|---|---|---|
| Fallow | Straight row | - | 77 | 86 | 91 | 94 |
| Row crops | Straight row | Poor | 72 | 81 | 88 | 91 |
| | Straight row | Good | 67 | 78 | 85 | 89 |
| | Contoured | Poor | 70 | 79 | 84 | 88 |
| | Contoured | Good | 65 | 75 | 82 | 86 |
| | Terraced | Poor | 66 | 74 | 80 | 82 |
| | Terraced | Good | 62 | 71 | 78 | 81 |
| Small grain | Straight row | Poor | 65 | 76 | 84 | 88 |
| | Straight row | Good | 63 | 75 | 83 | 87 |
| | Contoured | Poor | 63 | 74 | 82 | 85 |
| | Contoured | Good | 61 | 73 | 81 | 84 |
| | Terraced | Poor | 61 | 72 | 79 | 82 |

Table 11.3: Runoff curve number for hydrologic soil-cover complexes for antecedent rainfall condition II and $I_a$=2S (Cont.)

| Land use or crop | Treatment or practice | Hydrologic condition | Hydrologic soil group A | B | C | D |
|---|---|---|---|---|---|---|
| | Terraced | Good | 59 | 70 | 78 | 81 |
| Close-seeded legumes | Straight row | Poor | 66 | 77 | 85 | 89 |
| or rotation meadow | Straight row | Good | 58 | 72 | 81 | 85 |
| | Contoured | Poor | 64 | 75 | 83 | 85 |
| | Contoured | Good | 55 | 69 | 78 | 83 |
| | Terraced | Poor | 63 | 73 | 80 | 83 |
| | Terraced | Good | 51 | 67 | 76 | 80 |
| Pasture or range | | Poor | 68 | 79 | 86 | 89 |
| | | Fair | 49 | 69 | 79 | 84 |
| | | Good | 39 | 61 | 74 | 80 |
| | Contoured | Poor | 47 | 67 | 81 | 88 |
| Meadow (permanent) | | Good | 30 | 58 | 71 | 78 |
| Woods (farm woodlots) | | Poor | 45 | 66 | 77 | 83 |
| | | Fair | 36 | 60 | 73 | 79 |
| | | Good | 25 | 55 | 70 | 77 |
| Farmsteads | | - | 59 | 74 | 82 | 86 |
| Roads and right-of-way (hard surface) | | - | 74 | 84 | 90 | 92 |

## Determine the area-weighed curve number

The SCS method uses curve numbers. These numbers are related to the different land cover types, soil properties and the antecedent moisture. Within the catchment more than one land cover type and soil type exist. In order to find a representative curve number, an overall catchment curve number has to be determined using the areas of the different land cover and soil types as weighing factor.

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- Study the catchment area and determine the size of the total catchment area.
- Reclassify the soils map into a map showing the Hydrologic Soil Groups.
- Determine the Hydrologic soils group/Land cover complexes and determine the areas occupied by the different complexes.
- Select for each Hydrologic soils group/Land cover complex a curve number assuming antecedent rainfall condition II and $I_a$=0.2S.
- Calculate the overall catchment curve number.

## Determine the lag time

For the calculation of the lag time a number of watershed parameters have to be determined.

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- Calculate the Hydraulic watershed length.
- Determine the average watershed land slope.
- Calculate the lag time $t_{lag}$.

### Determine the unit duration of excess rainfall

The application of the SCS dimensionless unit hydrograph is only valid for storms with a duration less than 0.133 x time of concentration.

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- Calculate the duration D of excess rainfall using
  `D=0.133*Tc`.

### Determine the peak runoff rate for 1 cm of excess rainfall

When calculating the peak runoff of any unit hydrograph the amount of excess rainfall equals a unit depth, i.e. 1 mm or 1 cm. Based on the unit hydrograph the peak flow rate for other storms with a different rainfall excess amount can be calculated.

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- Calculate the peak runoff rate for a total amount of excess rainfall of 1 cm.

## References

Schwab, G.O., Fangmeier, D.D., Elliot, W.J. and Freveret, R.K. (1993). *Soil and water conservation engineering*. J. Wiley and sons. New York. 507 pp.

Sherman, L.K. (1932). Stream-flow from rainfall by the unit-graph method. *Eng. News-Rec.* 108: 501-505.

U.S. Soil Conservation Service. (1964). *Hydrology*. Section 4, SCS National Engineering Handbook. Washington, D.C.