CEGE 4501 Hydrologic Design

Chapter 6:
Surface Water and Runoff Processes

UNIVERSITY OF MINNESOTA
Driven to Discover[SM]

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Outline

Horton Stream Ordering I

Watershed and runoff: As review, a **"watershed"**, a catchment or a drainage basin are three synonymous terms that define as a locus of all points on the earth's surface that drain precipitation water to a single point called the **"watershed outlet"**. Streams can be classified within a basin by systematic ordering the network of branches.

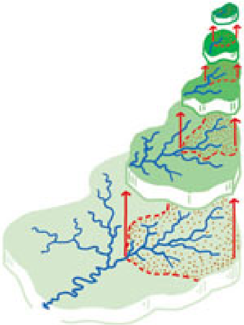


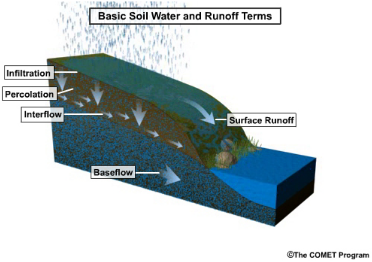
Figure 1: Left: Schematic of precipitation in a watershed flowing to the outlet point (Credit: The COMET Program). Right: A schematic of how watersheds are nested and watershed size varies depending on the basin outlet selected (right, credit: Marsh, 1998, p. 170)

Basics of Surface Runoff I

During a rainfall event, there are two types of water storages:

- **Detention Storages:** Short-term storages that are depleted by overland drainage/flows.
- **Retention Storages:** Long-term storages that are depleted by evaporation.

Surface runoff or overland flow is defined as the portion of rainfall, snowmelt, and/or irrigation water that runs over the soil surface toward the stream rather than infiltrating into the soil. The definition of runoff also include the interflow or subsurface stormflow, which together with the surface runoff makes up the volume of water that hydrologists generally refer to as total runoff.During a precipitation event the detention storages begin to fill and water begin flowing overland. Overland flows join together and form more concentrated flows that channelize the underlying soil creating the so-called "channel or stream network". Several channel networks eventually drain into the main stream and generate the streamflow.



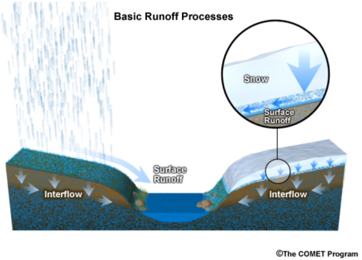


Figure 2: A schematic of the main hydrologic fluxes in streamflow.

Basics of Surface Runoff II

The flow that you see in a stream or river typically consists of three of the hydrologic fluxes we covered in Chapter 1: overland flow, interflow, and baseflow as shown in Figure 2

The overland flow component can be split into two categories:

- **Hortonian overland flow:** This overland flow occurs when precipitation rate is greater than infiltration capacity. It is also called "infiltration excess runoff".
- **Saturated overland flow:** This overland flow occurs when soil becomes saturated from below due to rise in the groundwater table.

Figure 3: The Hortonian (left) and Saturated (right) overland flow over the hill slope (Credit: The COMET Program).

Basics of Surface Runoff III

As we discussed, the infiltration rate is the water flux that enters the soil at the surface. It is often expressed as depth of water per time; for example, 10 millimeters per hour.

If precipitation rate is much higher than the infiltration capacity overland flow occurs immediately after the onset of precipitation. Infiltration excess is commonly observed with short-duration intense rainfall. It also occurs most often over land surfaces with high clay content or where the surface has been altered by soil compaction, urbanization, or fire.

However, when precipitation rate is less than or equal to infiltration capacity, no surface runoff occurs. For long enough low rate of precipitation, the water table may rise and produce the saturated overland flow from below. It is most common with long-duration, gentle-to-moderate rainfall, or because of successive precipitation and or snowmelt events.

Saturation excess overland flow can occur anywhere the soil is wet. It is most common in humid climates with gently sloped or flat basins. The saturate overland flow often begin to occur near the stream channel, where the groundwater depth is often shallower and it rises quickly in response to infiltrated water flux.

Figure 4: The Hortonian (left) and Saturated (right) overland flow on a column of soil (Credit: The COMET Program).

Streamflow Hydrograph I

The "streamflow hydrograph" is the the timeseries of flow rate at a specific location on a stream. We have already dealt with a hydrograph as part of the class projects. These measurements are typically captured at stream gauges, which measure flow rate based on river stage and a calculated/measured rating curve. The USGS is the primary source of stream gauge data in U.S.

For simplicity we will categorize two different hydrographs typically analyzed based on the time scale of interest. An "annual hydrograph" focuses on the flow over a time period of a year and typically the data will be aggregated to daily averages to smooth the hydrographs (shown below). A "storm hydrograph" focuses on the flow corresponding to a precipitation event for time periods rainging from hours to weeks depending on the watershed size.

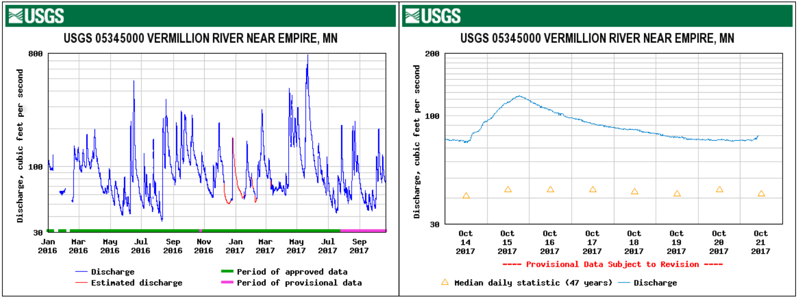


Figure 5: An example of an annual (left) and storm (right) hydrograph for Vermillion River near Empire, MN. (Credit: USGS).

Streamflow Hydrograph II

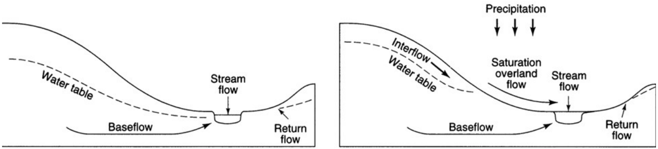


Figure 6: The main components of a streamflow in a dry period (left) and during a rainfall event (right) (from Mosley and McKerchar, 1993). The return flow occurs if the rate of interflow entering a saturated area from upslope exceeds the capacity for interflow to leave the area by flowing downhill through the soil. This often happens due to ground water ridges and the vicinity of streams.The excess interflow thus "returns" to the surface as runoff.

There are multiple characteristics of a a basin and its river network that determine the shape of the outflow hydrograph including: (a) the drainage basin, (b) slope, (c) hydraulic roughness, (d) natural and channel storages, (e) stream length, (f) channel density, (g) antecedent soil moisture, and (h) other factors such as land cover.

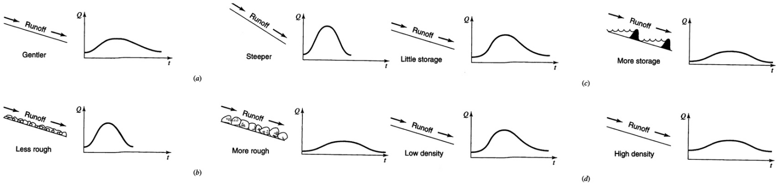


Figure 7: The effects of basin characteristics on the flood hydrograph (Masch 1984).

Streamflow Hydrograph III

The dynamics of precipitation events also affect the shape of the hydrograph.

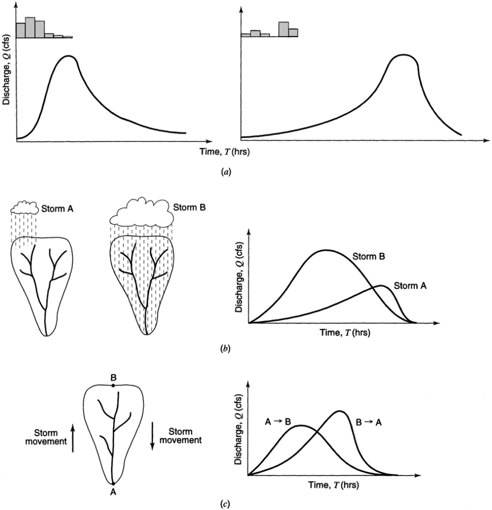


Figure 8: Effects of the shape of the rainfall hyetograph, storm size and movement on the shape of the streamflow hydrograph.

Streamflow Hydrograph IV

Hydrograph Components:

Hydrographs are typically divided into two components for analysis. The (a) Baseflow, which is the long-term contribution of groundwater flow to a stream hydrograph and the (b) direct runoff, which is the portion of the hydrograph that is in response to an excess rainfall of an event and is also referred to as quick flow. Common segments of a storm hydrograph can be typically divided into a few segments as follows:

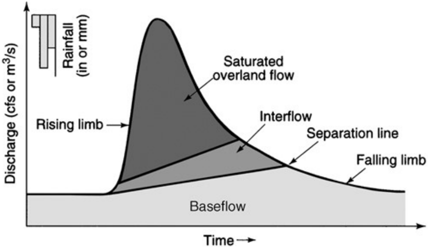


Figure 9: Main components of a storm hydrograph (McKerchar 1993). Note that the saturated overland flow and interflow form the direct runoff hydrograph.

Baseflow Separation:

Three differing methods for basflow separation are:

Straight line method: Draw a horizontal line from the beginning of the rising limb to end of the falling limb, where the recession starts.

Streamflow Hydrograph V

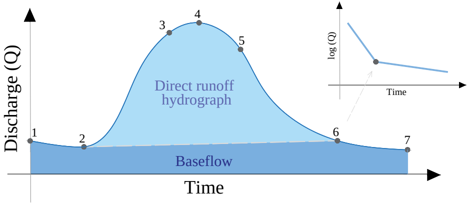


Figure 10: Components of the streamflow hydrograph: (1-2) baseflow recession, (2-3) rising limb , (3-5) crest segment, (4) peak flow , (5-6) falling limb, and (6-7) baseflow recession. The straight line method is used for baseflow septation.

Fixed base method: Draw a tangent line from the pre-event recession curve to the peak time and then connect it to a point on the hydrograph that the surface runoff is assumed to be negligible.

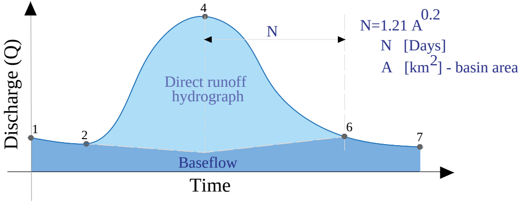


Figure 11: Fixed based method for baseflow septation.

Streamflow Hydrograph VI

Variable slope method: Draw a tangent line from the pre-event recession curve to the peak time and a tangent line from the post-event recession curve to the inflection point of the falling limb. A straightline is drawn between the peak discharge and inflection point.

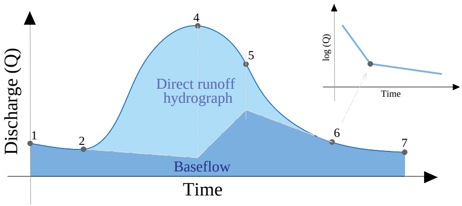


Figure 12: Variable slope method for baseflow septation.

Excess rainfall and direct runoff:

The direct runoff determined from a hydrograph *does not* exactly correspond to the volume of precipitation delivered over the basin since there are losses to storages. Therefore, when predicting direct runoff from precipitation inputs, we divide the rainfall hayetograph into:

- **Excess Rainfall:** The amount of rainfall that is neither retained on the land surface nor infiltrated into the soil (excluding interflow processes). This rainfall volume flows across the surface of the watershed and becomes direct runoff. Also known as *effective rainfall*.
- **Abstraction:** The rainfall that is absorbed primarily by *infiltration* as well as interception and surface storage. The excess rainfall hyetograph (ERH) is equal to the total rainfall minus abstraction largely due to infiltration to the ground. The relationships of rainfall, infiltration rate, and cumulative infiltration are shown in the following figures.

Streamflow Hydrograph VII

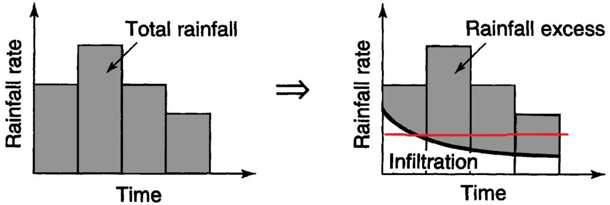


Figure 13: The concept of rainfall excess, which is the difference between the actual rainfall hyetograph and losses largely due to the infiltration. Generally, we either assume a constant rate (red line) or a time varying infiltration (black) rate in computation of the Excess rainfall hayetograph (ERH).

Excess Rainfall Determination I

Determining excess precipitation is crucial to predicting streamflow from future rainfall events. There are different methods for determining effective rainfall depending on whether streamflow data is available or not.

Determining Excess Rainfall using Streamflow Data:

Regardless of the method used, the first step is to separate the baseflow from the **direct runoff hydrograph (DRH)**. One of the most common methods for obtaining the ERH is the **"ϕ-Index Method"**. This method assumes a **constant rate of abstraction** throughout the storm event and is calculated as follows:

$$r_d = \sum_{m=1}^{M} (R_m - \phi \triangle t) = \sum_{m=1}^{M} R_m - M\phi\triangle t$$

where r_d $[mm]$ is the excess runoff depth, R_m $[mm]$ is the observed rainfall depth over selected time interval with decreasing order $R_1 > R_2 > \ldots, \triangle t$, M is the number of rainfall pulses that contribute to direct runoff, and ϕ $[mm/hr]$ is the constant abstraction rate.

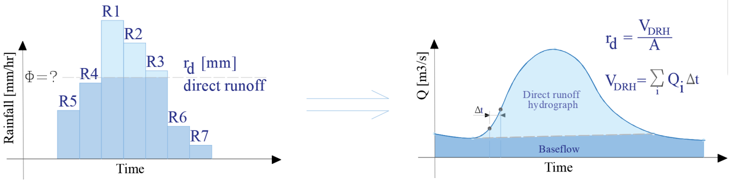


Figure 14: A schematic representation of the ϕ-index method. The Q_i are the result of direct runoff, which are obtained by subtracting the baseflow form the total observed flow.

Excess Rainfall Determination II

The process consists of checking the above equation for descending values of R_m until a positive ϕ value is achieved. Then double check that the depth of excess rainfall equals the depth of direct runoff. An example can be presented using the following information of a rainfall storm over a watershed area of 7.03 mile^2 with a baseflow of 400 [cfs] (Chow et al. 1988):

Rainfall and streamflow data dapted from the storm of May 24–25, 1981, on Shoal Creek at Northwest Park, Austin, Texas

	Time	Observed Rainfall (in)	Observed Streamflow (cfs)	Time ($\frac{1}{2}$ h)	Excess rainfall hyetograph (ERH) (in)	Direct runoff hydrograph (DRH) (cfs)
Column:	1	2	3	4	5	6
24 May	8:30 P.M.		203			
	9:00	0.15 (R6)	246			
	9:30	0.26 (R4)	283			
	10:00	1.33 (R3)	828	1	1.06 =1.33-0.27	428
	10:30	2.20 (R1)	2323	2	1.93 =2.20-0.27	1923
	11:00	2.08 (R2)	5697	3	1.81 =2.08-0.27	5297
	11:30	0.20 (R5)	9531	4		9131
25 May	12:00 A.M.	0.09 (R7)	11025	5		10625
	12:30		8234	6		7834
	1:00		4321	7		3921
	1:30		2246	8		1846
	2:00		1802	9		1402
	2:30		1230	10		830
	3:00		713	11		313
	3:30		394			
	4:00		354	Total	4.80	43550
	4:30		303			

Excess rainfall = observed rainfall − abstractions (0.27 in per half-hour)

Direct runoff = observed streamflow − baseflow (400 cfs)

Excess Rainfall Determination III

Calculation:

$$V_{\text{runoff}} = \Sigma Q_n \Delta t = 43,500[\text{cfs}] \times 1/2[\text{hr}] \times 3600\,[\text{s/hr}] = 7.839 \times 10^7\,[\text{ft}^3]$$

$$r_d = \frac{\mathrm{V_{runoff}}}{\text{Watershed area}} = \frac{7.84 \times 10^7\,[\text{ft}^3]}{7.03 \times 5280\,[\text{ft}^2]} = 4.8\,[\text{in}]$$

a) R_1

$$r_d = R_1 - \phi \Delta t$$
$$4.8 = 2.2 - \phi \times 0.5$$
$$\phi = -5.2\,[\text{in/hr}]$$ (not feasible)

b) R_1, R_2

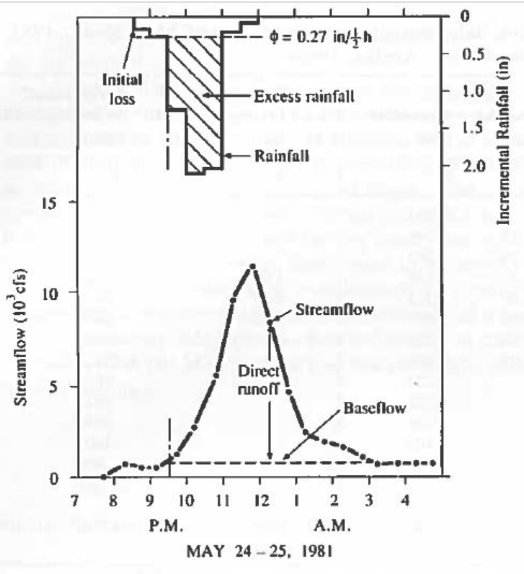
$$r_d = R_1 + R_2 - 2\phi \Delta t$$
$$4.8 = 2.2 - 2.08 - 2\phi \times 0.5$$
$$\phi = -0.52\,[\text{in/hr}]$$ (not feasible)

c) R_1, R_2, R_3

$$r_d = R_1 + R_2 + R_3 - 3\phi \Delta t$$
$$\phi = 0.54\,[\text{in/hr}] \rightarrow \phi = 0.27[\text{in/(0.5hr)}] \geq R_4 = 0.26\,[\text{in/(0.5hr)}]$$ (feasible)

If $\phi < R_4$ then we had to try $r_d = \Sigma_{i=1}^{4}(R_i - \phi \Delta t)$ and continue the process.

Excess Rainfall Determination IV



Excess Rainfall Determination V

For characterizing the amount of excess rainfall from stream data, we can also calculate the "runoff coefficient" (C):

$$C = \frac{r_d}{\sum_{n=1}^{N} R_n} = \frac{\text{Total Runoff}}{\text{Rainfall after the beginning of runoff}}$$

From the previous example we can easily calculate the runoff coefficient as:

$$C = \frac{4.8 \ in.}{(1.33 + 2.20 + 2.08 + 0.2 + 0.09) \ \ in.} = 0.81$$

the runoff coefficient is used extensively in engineering practice to determine the peak flow rate of a storm event based on average rainfall intensity over small watersheds through the "Rational Method":

$$Q = CiA$$

where Q is the peak flow rate [cfs], i is the average rainfall intensity [in/hr], and A is the basin area [acres]. *Note that the dimensions for the Rational Method do not match and it is purely an empirical relationship*. In practice, this method is used to design the size of catch basins and storm sewers by calculating the peak flow rate for a certain return period of rainfall event. There are standard estimates of the runoff coefficients based on different land cover such as Lawns (C=0.05-0.35), forest (0.05-0.25), concrete streets (0.7-0.95), and etc. This topic will be covered further later in the course.

Excess Rainfall Determination VI

Determining Excess Rainfall Using Infiltration Methods:

If streamflow data is not known, then we must resort to infiltration models to calculate the excess rainfall hyetograph. It is common to use infiltration models like *Green-Ampt* to estimate the ERH. The key assumption is that Direct Runoff = Precipitation - Infiltration.

Recall that the Green-Ampt infiltration rate is defined as:

$$f_t = K\left(1 + \frac{|\psi_f|\Delta\theta}{F_t}\right)$$

where f_t is $f(t)$, F_t is $F(t)$ and K is K_{sat} (saturated hydraulic conductivity). Additionally, we showed that the cumulative infiltration can be computed as follows:

$$F_t = Kt + |\psi_f| \cdot \Delta\theta \cdot \ln\left(1 + \frac{F_t}{|\psi_f|\Delta\theta}\right)$$

Now for the purpose of creating the ERH, *we must define cumulative infiltration after the ponding time*. To that end, we showed that:

$$F_{t_p+\Delta t} = F_{t_p} + K\Delta t + |\psi_f|\Delta\theta \ln\left(\frac{F_{t_p+\Delta t} + |\psi_f|\Delta\theta}{F_{t_p} + |\psi_f|\Delta\theta}\right)$$

where the cumulative infiltration at the time of ponding (t_p), was defined as follows:

$$F_{t_p} = \frac{K\Delta\theta|\psi_f|}{P_t - K}$$

Excess Rainfall Determination VII

As described in the following, finding ERH using infiltration method is an iterative process.

Algorithm for determination of infilteration and ponding time under variable rainfall intensity.

WHILE $t < t_r$ (t_r: the rainfall duration)

$$f_t = K\left(1 + \frac{|\psi_f|\Delta\theta}{F_t}\right)$$

IF $f_t > p_t$ (no ponding at time t)

$$F_{t+\triangle t} = p_t \cdot \Delta t \qquad f_{t+\triangle t} = K\left(1 + \frac{|\psi_f|\Delta\theta}{F_{t+\triangle t}}\right)$$

ELSE (ponding occurred)

$$F_{t+\Delta t} = F_t + K\Delta t + |\psi_f|\Delta\theta \ln\left(\frac{F_{t+\Delta t} + |\psi_f|\Delta\theta}{F_t + |\psi_f|\Delta\theta}\right)$$

$$f_{t+\Delta t} = K\left(1 + \frac{|\psi_f|\Delta\theta}{F_{t+\Delta t}}\right)$$

END

$t = t + \triangle t$

END

Excess Rainfall Determination VIII

An example:

Sandy Loam (Chow et al. 1988)

Ksat	1.09	[cm/hr]
Effective Saturation	0.4	
Effective Porosity	0.412	
ΔΘ	0.247	[cm]
|ψ|	11.01	[cm]

1	2	3	4	5	6	7	8	9
Time (min)	Incremental Rainfall (cm)	Cumulative Rainfall (cm)	Rainfall Intensity (cm/hr)	Theoretical Infiltration Rate (cm/hr)	Cumulative Infiltration (cm)	Cumulative Excess Rainfall (cm)	Incremental Excess Rainfall (cm)	Excess Rainfall Rate (cm/hr)
0	0	0	1.08	infinity	0			
10	0.18	0.18	1.26	17.57	0.18			
20	0.21	0.39	1.56	8.70	0.39			
30	0.26	0.65	1.92	5.65	0.65			
40	0.32	0.97	2.22	4.15	0.97			
50	0.37	1.34	2.58	3.30	1.34			
60	0.43	1.77	3.84	2.77	1.77		**Ponding Occurs**	
70	0.64	2.41	6.84	2.43	2.21	0.20	0.20	1.2239
80	1.14	3.55	19.08	2.23	2.59	0.96	0.75	4.5126
90	3.18	6.73	9.9	2.09	2.97	3.76	2.81	16.8463
100	1.65	8.38	4.86	1.99	3.31	5.07	1.30	7.8099
110	0.81	9.19	3.12	1.90	3.65	5.54	0.48	2.8750
120	0.52	9.71	2.52	1.84	3.96	5.75	0.20	1.2162
130	0.42	10.13	2.16	1.78	4.27	5.86	0.11	0.6814
140	0.36	10.49	1.68	1.74	4.57	5.92	0.06	0.3751
150	0.28	10.77	1.44	1.70	4.85		**Ponding Ends**	
160	0.24	11.01	1.14	1.67	5.09			
170	0.19	11.2	1.02	1.65	5.28			
180	0.17	11.37		1.63	5.45			

Excess Rainfall Determination IX

Below is a plot generated in MATLAB showing the results of the example problem. Notice that all abstractions before the time of ponding (where surface runoff is generated) is labeled **"initial abstractions"**. After t_p, everything above the green line is effective rainfall and everything below is infiltrated (losses).

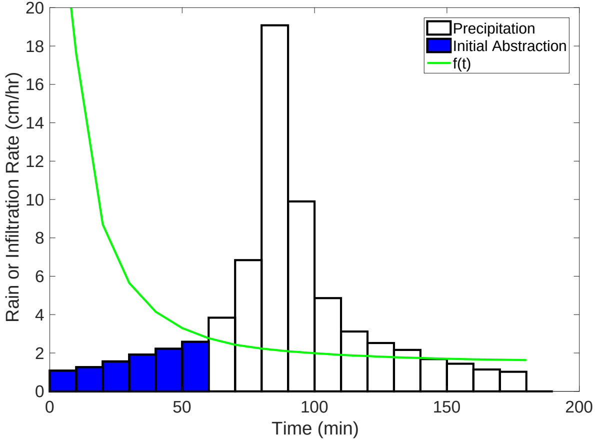


Figure 15: Solution plot to Green-Ampt example.

Excess Rainfall Determination X

SCS Method for runoff calculation:

The old USDA Soil Conservation Service (SCS; now called USDA-NRCS) created a runoff estimation method based on the following hypothesis shown by the components in Figure 16:

$$\frac{\text{Infiltrated water}}{\text{Total retention capacity}} = \frac{\text{produced surface runoff}}{\text{Total available water for surface runoff}}$$

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \qquad \textit{hypothesis} \tag{1}$$

P: Total precipitation [L]

I_a: Initial abstraction [L]

P_e: Excess Precipitation [L]

F_a: Water retained in the watershed [L]

S: maximum retention storage [L]

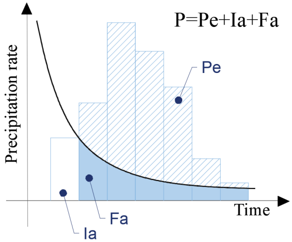


Figure 16: Schematic of the hydrograph components for the SCS method.

Excess Rainfall Determination XI

Equation 1 can be written as follows:

$$\frac{P - P_e - I_a}{S} = \frac{P_e}{P - I_a}$$

and thus

$$P_e = \frac{(P - I_a)^2}{P - I_a + S}$$

From data of field experiments for small watersheds, we can assume $I_a = 0.2S$, which leads to the following expression of excess precipitation:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S}.$$

Experimental results allowed parameterization of S using a **"curve number"**, which describes the retention capacity of differing landscapes:

$$S = \frac{1000}{CN} - 10 \qquad \text{[inches]}$$

where CN is called the curve number $0 \leq CN \leq 100$

$$CN = 100 \text{ (Impervious surfaces)}$$

$$CN < 100 \text{ (Natural surfaces).}$$

Excess Rainfall Determination XII

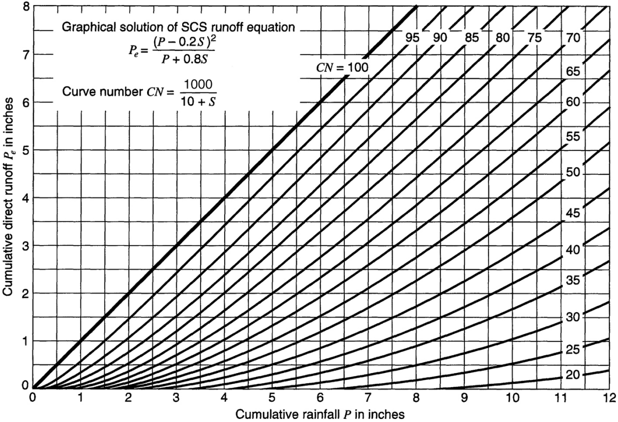


Figure 17: Solution of the SCS runoff equations for *normal* soil moisture condition (from U.S. Department of Agricultural Soil Conservation Service (1972).

The CN depends on:

- the antecedent moisture condition (AMC)
- soil type
- land use.

Excess Rainfall Determination XIII

The curve number in Figure 17 are for normal antecedent moisture conditions (AMC II). The soil moisture conditions for SCS method are defined as follows:

Classification of Antecedent Moisture Classes (AMC) for the SCS Method of Rainfall Abstractions

	Total 5-day antecedent rainfall (in)	
AMC group	Dormant season	Growing season
I	Less than 0.5	Less than 1.4
II	0.5 to 1.1	1.4 to 2.1
III	Over 1.1	over 2.1

Source: U.S. Department of Agriculture Soil Conservation Service (1972).

Figure 18: Definitions of AMC based on 5-day anecedent rainfall.

Therefore, correction factors are necessary for the dry and wet conditions as follows:

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)} \qquad (dry)$$

$$CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)} \qquad (wet)$$

The CN values also depend on the **soil type**, which the USDA has grouped into four categories:

- **Group A**: Deep sand, deep loess, aggregated silt (lower CN values, higher retention)
- **Group B**: Shallow loess, sandy loam
- **Group C**: Clay, loam, clayey loam
- **Group D**: Soils with heavy content of clay (high CN values, low retention)

Excess Rainfall Determination XIV

Runoff Curve Numbers (Average Watershed Condition, $I_a = 0.2S$)

Land use description			Curve numbers for hydrologic soil group			
			A	B	C	D
Fully developed urban areas[a] (vegetation established)						
Lawns, open spaces, parks, golf courses, cemeteries, etc.						
Good condition; grass cover on 75% or more of the area			39	61	74	80
Fair condition; grass cover on 50% to 75% of the area			49	69	79	84
Poor condition; grass cover on 50% or less of the area			68	79	86	89
Paved parking lots, roofs, driveways, etc.			98	98	98	98
Streets and roads						
Paved with curbs and storm sewers			98	98	98	98
Gravel			76	85	89	91
Dirt			72	82	87	89
Paved with open ditches			83	89	92	93
		Average % impervious[b]				
Commercial and business areas		85	89	92	94	95
Industrial districts		72	81	88	91	93
Row houses, town houses, and residential with lot sizes 1/8 acre or less		65	77	85	90	92
Residential: average lot size						
1/4 acre		38	61	75	83	87
1/3 acre		30	57	72	81	86
1/2 acre		25	54	70	80	85
1 acre		20	51	68	79	84
2 acre		12	46	65	77	82
Developing urban areas[c] (no vegetation established)						
Newly graded area			77	86	91	94
Cover						
Land use	Treatment of practice	Hydrologic condition[d]				
Cultivated agricultural land						
Fallow	Straight row		77	86	91	94
	Conservation tillage	Poor	76	85	90	93
	Conservation tillage	Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Conservation tillage	Poor	71	80	87	90

Excess Rainfall Determination XV

(*Continued*)

Cover		Hydrologic condition[d]	Curve numbers for hydrologic soil group			
Land use	Treatment of practice		A	B	C	D
	Conservation tillage	Good	64	75	82	85
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured and conservation	Poor	69	78	83	87
	tillage	Good	64	74	81	85
	Contoured and terraces	Poor	66	74	80	82
	Contoured and terraces	Good	62	71	78	81
	Contoured and terraces	Poor	65	73	79	81
	and conservation tillage	Good	61	70	77	80
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Conservation tillage	Poor	64	75	83	86
	Conservation tillage	Good	60	72	80	84
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured and conservation	Poor	62	73	81	84
	tillage	Good	60	72	80	83
	Contoured and terraces	Poor	61	72	79	82
	Contoured and terraces	Good	59	70	78	81
	Contoured and terraces	Poor	60	71	78	81
	and conservation tillage	Good	58	69	77	80
Close-seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured and terraces	Poor	63	73	80	83
	Contoured and terraces	Good	51	67	76	80
Noncultivated agricultural land, pasture or range	No mechanical treatment	Poor	68	79	86	89
	No mechanical treatment	Fair	49	69	79	84
	No mechanical treatment	Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow		—	30	58	71	78
Forested—grass or orchards—evergreen or deciduous		Poor	55	73	82	86
		Fair	44	65	76	82
		Good	32	58	72	79
Brush		Poor	48	67	77	83
		Good	20	48	65	73
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		—	59	74	82	86
Forest-range						
Herbaceous		Poor		79	86	92
		Fair		71	80	89
		Good		61	74	84

Excess Rainfall Determination XVI

(*Continued*)

Cover		Hydrologic condition[d]	Curve numbers for hydrologic soil group			
Land use	Treatment of practice		A	B	C	D
Oak–aspen		Poor		65	74	
		Fair		47	57	
		Good		30	41	
Juniper–grass		Poor		72	83	
		Fair		58	73	
		Good		41	61	
Sage–grass		Poor		67	80	
		Fair		50	63	
		Good		35	48	

[a]For land uses with impervious areas, curve numbers are computed assuming that 100% of runoff from impervious areas is directly connected to the drainage system. Pervious areas (lawn) are considered to be equivalent to lawns in good condition and the impervious areas have a *CN* of 98.

[b]Includes paved streets.

[c]Use for the design of temporary measures during grading and construction. Impervious area percent for urban areas under development vary considerably. The user will determine the percent impervious. Then using the newly graded area *CN* and Figure 8.7.1*a* or *b*, the composite *CN* can be computed for any degree of development.

[d]For conservation tillage in poor hydrologic condition, 5 percent to 20 percent of the surface is covered with residue (less than 750-lb/acre row crops or 300-lb/acre small grain).

For conservation tillage in good hydrologic condition, more than 20 percent of the surface is covered with residue (greater than 750-lb/acre row crops or 300-lb/acre small grain).

[e]Close-drilled or broadcast.

For noncultivated agricultural land:

Poor hydrologic condition has less than 25 percent ground cover density.

Fair hydrologic condition has between 25 percent and 50 percent ground cover density.

Good hydrologic condition has more than 50 percent ground cover density.

For forest–range:

Poor hydrologic condition has less than 30 percent ground cover density.

Fair hydrologic condition has between 30 percent and 70 percent ground cover density.

Good hydrologic condition has more than 70 percent ground cover density.

Source: U.S. Department of Agriculture Soil Conservation Service (1986).

Figure 19: Runoff curve numbers (average watershed condition, $I_a = 0.2S$, USDA, 1986)

Excess Rainfall Determination XVII

The curve number in the above tables are for average watershed ($I_a = 0.2S$) and normal antecedent moisture condition (AMC II). For watersheds with several sub-catchments with different CNs, the area-averaged composite values of CN shall be computed.

Example: Compute runoff from 5 inches of rainfall on a 1000-acre watershed. Hydrologic soil type is 50% (B) and 50%(C). The watershed land use is:

80% residential area that is 30% impervious

20% paved roads with curbs and storm sewers

Land use	Hydrologic soil group			
	B		C	
	%	CN	%	CN
Residential (30% impervious)	40	72	40	81
Roads	10	98	10	98

$\text{CN(II)} = \frac{40\times72+10\times98+40\times81+10\times98}{40+10+40+10} = 80.80$

$\text{S} = \frac{1000}{CN} - 10 = 2.38 \quad \text{[in]}$

$P_e = \frac{(P-0.2S)^2}{(P+0.8S)} = 2.96 \quad \text{[in]}$

for wet condition:

$CN(III) = \frac{23CN(II)}{10+0.13CN(II)} = 90.6$

and the calculation continues ...

Surface Flow and Velocity I

Surface runoff in a watershed occurs first as a thin sheet of overland flow in the upper slopes for a short distance ($<$ 100 ft) and then eventually produce or merge to the channel flow that you see in gullies, streams and rivers. The goal for this section is to briefly quantify the properties of overland sheet flow.

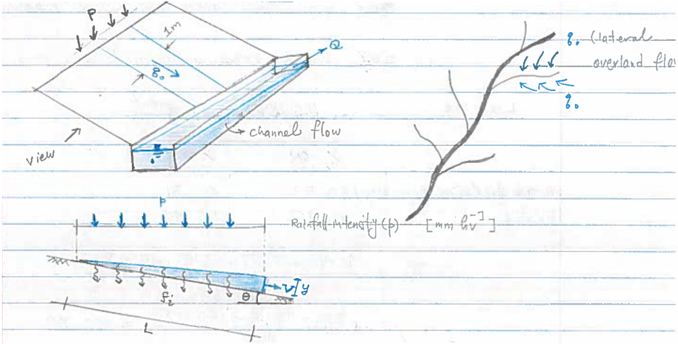


Figure 20: Overland flow to the streams and modeling concepts.

Here p is precipitation intensity [L/T], θ is the surface slope, f_i is infiltration rate [L/T], V is average velocity [L/T], L is slope length [L], S_0 is slope [L/L], and y is the flow depth [L].

Let's write a mass balance or continuity equation for the above control volume as follows:

Surface Flow and Velocity II

Inflow: $p\,L\,\cos\theta$ (precipitation)

Outflow: $f_i\,L\,\cos\theta$ (infiltration)

Outflow: $q_0 = V\,y$ (discharge per unit width)

Conservation of mass results in $p\,L\,\cos\theta = f_i\,L\,\cos\theta + V\,y$.

Note that in the above expression the unit is in terms of discharge per unit width [L^2 T^{-1}]. Thus, the overland flow per unit width at the end of the slope is:

$$q_0 = V\,y = (p - f_i)\,L\,\cos\theta$$

Recall: From the Darcy-Weisbach equation we have

$$h_f = f\,\frac{L}{D}\,\frac{V^2}{2g}$$

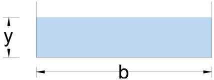
where f is the friction coefficient [-], L: pipe length [L]; D: pipe diameter [L]; V: Velocity [L T^{-1}]; and h_f: head loss [L].

By definition, the hydraulic radius in pipe or channel is defined as: $R = \frac{A}{P}$

A: wetter area [L^2]

P: wetted perimeter [L]

Surface Flow and Velocity III



For a rectangular channel we have : $R = \frac{by}{b+2y} \simeq y$ (when $b \gg 2y$). Recall that for a pipe $R = \frac{\pi D^2/4}{\pi D} = \frac{D}{4}$ and thus in a pipe $D = 4R$.

Laminar Overland Flow

Next we need to use the conservation of momentum to define the average velocity and height of the overland sheet flow. These equations depend on whether flow is **"laminar"** (parallel streamlines) or **"turbulent"** (mixed by eddies), which is determined by the flow Reynold's number:

$$Re = \frac{VD}{\nu} = \frac{4V\,R}{\nu} \quad \text{(pipe)} \qquad Re = \frac{4V\,y}{\nu} = \frac{4q_0}{\nu} \quad \text{(wide rectangular channel)}$$

where ν is kinematic viscosity [L^2T^{-1}]. We know from fluid mechanics that generally when Re <2000, flow is laminar. Recall that from the Moody digram, we have $f = \frac{64}{R_e}$ for laminar flow in pipes; however, for uniform overland sheet flow, the following formula shall be used for laminar overland sheet flow (Chow 1998):

$$f = \frac{C_L}{R_e}$$

$$C_L = 96 + 108\,p^{0.4}$$

where p is the precipitation rate [in hr^{-1}].

Surface Flow and Velocity IV

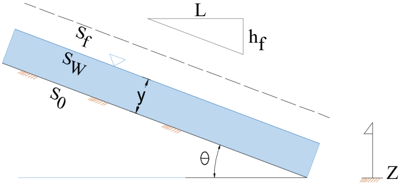


Figure 21: Recall that the Energy grade line is EGL$=z+\frac{V^2}{2g}+\frac{p}{\rho_w\, g}$ and for a uniform flow we have $S_f=S_w=S_0=h_f/L$.

From the Darcy-Weisbach equation $S_0=\frac{h_f}{L}=\frac{f}{4y}\frac{V^2}{2g}$ and $q_0=Vy$, then we have

$$S_0=\frac{f}{4y}\frac{q_0^2}{2gy^2}=\frac{f}{8gy^3}q_0^2$$

$$y^3=\frac{f}{8gs_0}q_0^2 \Longrightarrow y=\left(\frac{fq_0^2}{8gS_0}\right)^{1/3}$$

where $q_0=(p-f_i)\,L\cos\,\theta$.

Surface Flow and Velocity V

Turbulent Overland Flow

Once overland flow becomes turbulent ($Re > 2000$), the roughness factor f becomes independent of the Reynolds number, and the popular Manning's Equation can be used to explain the velocity of overland sheet flow as follows:

$$V = \frac{1.49}{n} R^{2/3} S_0^{1/2} \qquad (US\ units) \qquad V = \frac{1}{n} R^{2/3} S_0^{1/2} \qquad (SI\ units)$$

where n is Manning's roughness coefficient and $R = y$ is the hydraulic radius for a wide open channel. The Manning coefficient, is an "empirically" derived coefficient, which is dependent on many factors, including surface roughness and sinuosity. T

Substitute $V = q_0/y$ into Manning's equation one can obtain:

$$y = \left(\frac{n q_0}{1.49 S_0^{1/2}} \right)^{3/5} \qquad (US\ units) \qquad y = \left(\frac{n q_0}{S_0^{1/2}} \right)^{3/5} \qquad (SI\ units)$$

Typical values for Manning's coefficients n for overland flow are given on the next slide. These values are valid to depths of about 0.1 ft.

Surface Flow and Velocity VI

Roughness coefficients (Manning's n) for sheet flow

Surface description	n [1]
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤20%	0.06
Residue cover >20%	0.17
Grass:	
Short grass prairie	0.15
Dense grasses [2]	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods: [3]	
Light underbrush	0.40
Dense underbrush	0.80

1 The n values are a composite of information compiled by Engman (1986).

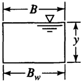
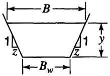
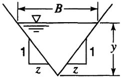
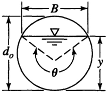
2 Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

3 When selecting n , consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

Figure 22: Typical values of Manning roughness coefficient (n) for overland flow.

Surface Flow and Velocity VII

Table 5.1.2 Geometric Functions for Channel Elements

Section:	Rectangle	Trapezoid	Triangle	Circle
				
Area A	$B_w y$	$(B_w + zy)y$	zy^2	$\frac{1}{8}(\theta - \sin\theta)d_o^2$
Wetted perimeter P	$B_w + 2y$	$B_w + 2y\sqrt{1+z^2}$	$2y\sqrt{1+z^2}$	$\frac{1}{2}\theta d_o$
Hydraulic radius R	$\frac{B_w y}{B_w + 2y}$	$\frac{(B_w + zy)y}{B_w + 2y\sqrt{1+z^2}}$	$\frac{zy}{2\sqrt{1+z^2}}$	$\frac{1}{4}\left(1 - \frac{\sin\theta}{\theta}\right)d_o$
Top width B	B_w	$B_w + 2zy$	$2zy$	$\left[\sin\left(\frac{\theta}{2}\right)\right]d_o$ or $2\sqrt{y(d_o - y)}$
$\frac{2dR}{3Rdy} + \frac{1}{A}\frac{dA}{dy}$	$\frac{5B_w + 6y}{3y(B_w + 2y)}$	$\frac{(B_w + 2zy)\left(5B_w + 6y\sqrt{1+z^2}\right) + 4zy^2\sqrt{1+z^2}}{3y(B_w + zy)\left(B_w + 2y\sqrt{1+z^2}\right)}$	$\frac{8}{3y}$	$\frac{4(2\sin\theta + 3\theta - 5\theta\cos\theta)}{3d_o\theta(\theta - \sin\theta)\sin(\theta/2)}$ where $\theta = 2\cos^{-1}\left(1 - \frac{2y}{d_o}\right)$

Source: Chow (1959) (with additions).

Figure 23: Hydraulic radius formulas for simple open channel geometries.

Surface Flow and Velocity VIII

Travel Time

One main reason for defining the velocity of these runoff mechanisms is to determine the **"travel time"** in a basin. As you know, travel time can be inferred from a distance and a velocity as follows:

$$\triangle t = \sum_{i=1}^{N} \frac{l_i}{V_i}$$

Every point within a watershed will have a travel time based on its flowpath to the outlet. When rainfall begins, the areas with the shortest travel times are contributing to the flow at the outlet and, as the storm progresses, a larger area of the watershed contributes until the exact time when all area in the watershed is contributing to flow at the outlet. This time scale is known as the "time of concentration (t_c)" and can also be defined as the travel time from the hydrologically most distant point in the watershed. We will touch on this topic further in the next chapter.

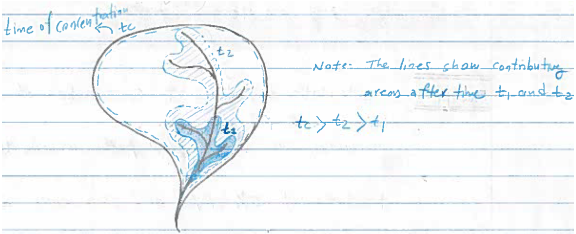


Figure 24: Schematic showing the growing contributing areas and the time of concentration.

Surface Flow and Velocity IX

Description of water course	Slope in percent			
	0-3	4-7	8-11	12-
Unconcentrated				
Woodlands	0-1.5	1.5-2.5	2.5-3.25	3.25-
Pastures	0-2.5	2.5-3.25	3.5-4.25	4.25-
Cultivated	0-3.0	3.0-4.5	4.5-5.5	5.5-
Pavements	0-8.5	8.5-13.5	13.5-17	17-
Concentrated				
Outlet channels (Manning Equation)				
Natural channel not well defined	0-2	2-4	4-7	7-

Table 1: Approximate average velocities in ft/s of runoff flow for calculating time of concentration. The unconcentrated condition occurs in the upper part of the watershed prior to the overland flows accumulating in a channel. Note that the concentrated manning coefficients are very rough estimate for an unknown channel condition, which may vary with channel size and conditions (From drainage manual, Texas highway department, 1970

There are many basin characteristics that effect the travel time and time of concentration. The next few figures are illustrations of how basin shape, size, slope, and stream meandering characteristics can affect travel time (Credit for following figures: The COMET Program).

Surface Flow and Velocity X

Surface Flow and Velocity XI

Surface Flow and Velocity XII

Surface Flow and Velocity XIII

Horton Laws of Stream Network I

We will now briefly cover some basics of the stream network. One of the most common ways to organize the complex configuration of connected stream reaches in a river network is using "Horton Stream Ordering". Basically, the channels furthest upstream that have no channels flowing into them are order 1. Then if two or more channels of a same order feed into a downstream reach, that reach becomes the next order, i.e., two order 1 streams feed into an order two streams. If two streams of different orders flow into another reach, that reach retains the highest order, i.e. an order 3 and order 1 stream feed into an order 3 stream.

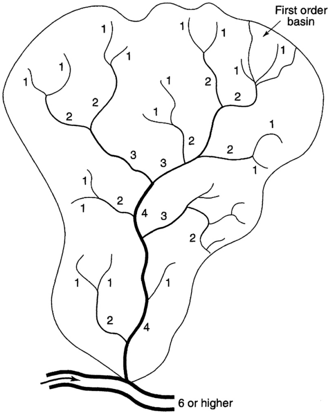


Figure 25: Example of Horton stream ordering (from Hewlett and Nutter, 1969)

Horton Laws of Stream Network II

Horton and others found some significant scaling relationships from this ordering. The bifurcation ratio of the stream network is found through "Horton's Law of Stream Numbers":

$$\frac{N_i}{N_{i+1}} = R_B$$

where N_i is the number of streams with order i. The bifurcation ratio, R_B, has typical values ranging from 3 to 5. The next scaling law is"Horton's Law of Stream Length":

$$\frac{L_{i+1}}{L_i} = R_L$$

where L_i is the average length of streams with order i. Furthermore, one of the most important findings to hydrology is "Horton's Law of Stream Contributing Area":

$$\frac{A_{i+1}}{A_i} = R_A$$

where A_i is the average contributing area of streams with order i.

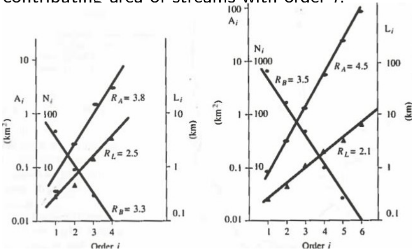


Figure 26: Example of Stream Laws from nested Mamon basins (Valdes et al., 1979).