Surface Water Hydrology Professor. Rajib Maity Department of Civil Engineering Indian Institute of Technology, Kharagpur Lecture 16 Infiltration Indices

(Refer Slide Time: 0:14)

Concepts Covered ≻Infiltration Indices ≻φ-Index ≻W-Index	Precipitation Interception Infiltration Infiltration Percolation Ground water recharge Ground water flow Base flow Sector Flow
Surface Water Hydrology: M02L16	Dr. Rajib Maiy, IIT Kharagour 2

In this specific lecture, we will discuss the infiltration indices. So, under this concept cover, two important concepts that will be covered one is $\boldsymbol{\varphi}$ index and W-index.

(Refer Slide Time: 0:36)



The outline of this lecture goes as follows an introduction to Infiltration indices and then we take $\boldsymbol{\varphi}$ index and W-index one after another and we will also give their introduction then the procedure to estimation of $\boldsymbol{\varphi}$ index and W-index will be discussed one after another. Then some brief discussion on the practical use of Infiltration indices before we proceed to summary.

(Refer Slide Time: 1:02)

Infiltration Indices

- In many hydrological applications, such as hydrograph analysis, flood analysis, etc., it is convenient to use a <u>constant average value of infiltration rate</u> for the entire storm duration.
- This constant average rate of infiltration is called infiltration index.
- · Two infiltration indices commonly used are:



Infiltration Indices

In many hydrological applications, such as hydrograph analysis, flood analysis, etc., it is convenient to use a constant average value of infiltration rate for the entire storm duration. This constant average rate of infiltration is called the infiltration index. So, there are two commonly used indices are as follows, one is $\boldsymbol{\varphi}$ index and the other one is W-index.

(Refer Slide Time: 2:07)



φ-Index

The φ -index is the constant average rate of infiltration above which the total rainfall volume (also known as rainfall excess) is equal to the runoff volume. In other words, it is the constant rate of infiltration that will yield an excess rainfall hyetograph of total depth equal to the

depth of direct runoff over the catchment. The φ -index is derived from the rainfall hyetograph with the knowledge of the resulting runoff volume.

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 The initial loss is also included in the infiltration loss, calculated through φ-index. The amount of rainfall in excess of the φ-index is called excess rainfall or rainfall excess or 	40 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5
effective rainfall. Rainfall intensity $< \varphi$ -index	⁴ 2 _{0.5} 0 0.5 1 15 2 2.5 3 3.5 4 4. Time (h)
Rainfall intensity > φ -index = Runoff in	agnitude – φ -index a a time interval

The initial loss is also included in the infiltration loss, calculated through φ -index. The amount of rainfall in excess of the φ -index is called excess rainfall or rainfall excess of effective rainfall.

Rainfall intensity $< \varphi$ -index

Infiltration rate = Rainfall intensity

Rainfall intensity > φ -index

Rainfall magnitude – φ -index = Runoff in a time interval

(Refer Slide Time: 4:17)



Procedure for estimation of ϕ -index

Consider a rainfall hyetograph of event duration *D* hours. There are *N* (i.e., *N*=9, as shown in Fig. 1) pulses of time interval Δt such that $N \times \Delta t = D$.

- I_i = Intensity of rainfall in i^{th} pulse
- t_{e} = Duration of rainfall excess
- R_d=Total direct runoff,

Total rainfall amount $P = \sum_{i=1}^{N} I_i \Delta t$



Fig.1 shows the φ index

(Refer Slide Time: 5:36)

<i>φ</i> -index
Procedure for estimation of φ -index
If rainfall hyetograph and total runoff depth are given, then φ -index of the storm can be determined by trial-and-error procedure.
1. Assume that out of given N pulses, M number of pulses have rainfall excess (Note: $M \le N$). Select M number of pulses in decreasing order of rainfall intensity, I_i .
2. Find the value of φ , that satisfies the relation, $R_d = \sum_{1}^{M} (l_i - \varphi) \Delta t$
3. Using the value of φ from Step 2, find the number of pulses (M_c) , which give rainfall excess. $(M_c = $ number of pulses with rainfall intensity $I_i \ge \varphi)$
4. If $M_c = M$, then φ of Step 2 is the correct value of φ -index. If not, repeat the procedure from Step 1 onwards with new value of
M (considering the result from Step 3 as a reference).
4. If $M_c = M$, then φ of Step 2 is the correct value of φ -index. If not, repeat the procedure from Step 1 onwards with new value of <i>M</i> (considering the result from Step 3 as a reference).

If rainfall hyetograph and total runoff depth are given, then φ -index of the storm can be determined by trial-and-error procedure.

1. Assume that out of given N pulses, M number of pulses have rainfall excess.

(Note: $M \leq N$). Select M number of pulses in decreasing order of rainfall intensity, I_i .

$$R_d = \sum_{1}^{M} (I_i - \varphi) \Delta t$$

- 2. Find the value of φ , that satisfies the
- 3. Using the value of φ from Step 2, find the number of pulses (M_c), which give rainfall excess. (M_c = number of pulses with rainfall intensity $I_i \ge \varphi$)
- 4. If $M_c = M$, then φ of Step 2 is the correct value of φ -index. If not, repeat the procedure from Step 1 onwards with the new value of M (considering the result from Step 3 as a reference).

(Refer Slide Time: 8:00)



Example 16.1

A storm with 10.5 cm of precipitation produced a direct runoff of 6.5 cm. The duration of the rainfall was 16 hours and its time distribution is given below. Estimate the φ -index of the storm.

Time from start (h)	0	2	4	6	8	10	12	14	16
Cumulative rainfall (cm)	0	0.4	1.6	3.0	5.2	7.35	8.4	9.45	10.50

Solution





(Refer Slide Time: 8:55)

Pulse number	Time from start of rain (h)	Cumulative rainfall (cm)	Incremental rainfall (cm)	Intensity of rainfall, <i>l</i> _i (cm/h)	
1	2	0.40	0.40	0.20 *	
2	4	1.60	1.20	0.60	
3	6	3.00	1.40	0.70	
4	8	5.20	2.20	1.10	
5	10	7.35	2.15	1.07	
6	12	8.40	1.15	0.58	
7	14	9.45	1.05	0.52	
8	16	10.50	1.05	0.52	

Considering time interval, $\Delta t=2$ h, the rainfall intensities are calculated

Pulse number	Time from start of rain (h)	Cumulative rainfall (cm)	Incremental rainfall (cm)	Intensity of rainfall, <i>I_i</i> (cm/h)
1	2	0.40	0.40	0.20
2	4	1.60	1.20	0.60
3	6	3.00	1.40	0.70
4	8	5.20	2.20	1.10
5	10	7.35	2.15	1.07
6	12	8.40	1.15	0.58
7	14	9.45	1.05	0.52
8	16	10.50	1.05	0.52

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= 16 hours, Δt = 2 hours and N = 8 41 uming M = 8, t _e =M × Δt = 16 hours the M = N, all the pulses are included. the fl, R _d = $\sum_{i=1}^{n} (l_i - \varphi) \Delta t$, 6.5 = $\sum_{i=1}^{n} l_i \Delta t - \varphi(8 × \Delta t)$ 6.5 = $\left[(0.2 × 2) + (0.60 × 2) + (0.70 × 2) + (1.10 × 2) + (1.07 × 2) + (0.58 × 2) + (0.52 × 2)$	411					
a1 1 summing $M = 8$, $t_e = M \times \Delta t = 16$ hours see $M = N$, all the pulses are included. noff, $R_d = \sum_{1}^{8} (l_i - \varphi) \Delta t$, $6.5 = \sum_{1}^{8} l_i \Delta t - \varphi(8 \times \Delta t)$ $6.5 = \left[(0.2 \times 2) + (0.60 \times 2) + (0.70 \times 2) + (1.10 \times 2) + (1.07 \times 2) \\ + (0.58 \times 2) + (0.52 \times 2) + (0.52 \times 2) \right] - 160$ $\varphi = \frac{10.58 - 6.5}{16} = 0.255$ cm/h = Number of pulses with rainfall intensity $M_c \ge \varphi$ e, $l_i \ge 0.255$ cm/h = Number of pulses with rainfall intensity $M_c \ge \varphi$ e, $l_i \ge 0.255$ cm/h Time from start R Hydrology: M02.16 Dr. Rajib Maity, IIT Khangper 11 tion nsidering time interval, $\Delta t = 2$ h, the rainfall intensities are calculated. Pulse Time from start of rain (h) Camulative nainfall (cm) rainfall (l, l, (cm/h)) 1 2 0.40 0.20 2 4 1.60 1.20 0.60 3 6 3.00 1.40 0.70 4 8 5.20 2.20 1.10	= 16 h c	ours, $\Delta t = 2$ hour	s and $N = 8$			
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ec $M = N$, all the pulses are included. noff, $R_d = \sum_1^8 (l_t - \varphi) \Delta t$, $6.5 = \sum_1^8 l_t \Delta t - \varphi(8 \times \Delta t)$ $6.5 = \begin{bmatrix} (0.2 \times 2) + (0.60 \times 2) + (0.70 \times 2) + (1.10 \times 2) + (1.07 \times 2) \\ + (0.58 \times 2) + (0.52 \times 2) + (0.52 \times 2) \end{bmatrix} - 160$ $\varphi = \frac{10.58 - 6.5}{16} = 0.255$ cm/h = Number of pulses with rainfall intensity $M_c \ge \varphi$ rer, $l_t \ge 0.255$ cm/h = kumber of pulses with rainfall intensity $M_c \ge \varphi$ rer, $l_t \ge 0.255$ cm/h is $T_s M_c = 7 \neq M$, hence assumed M is not correct. arer Hydrology: M02.16 Dr. Rajib Maiy, III Kharagor Intensities are calculated. Pulse Time from start quark of rain (h) Cumulative rainfall (cm) rainfall (cm) 1 2 2 4 1.60 1.20 3 6 3 6 3.00 1.40 4 8 5 10	suming	$M = 8, t_e = M \times L$	$\Delta t = 16$ hours			
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D=16 hours, $\Delta t=2$ hours and N=8

<u>Trial 1</u>

Assuming M = 8, $t_e = M \times \Delta t = 16$ hours

Since M = N, all the pulses are included.

Runoff, $R_d = \sum_{1}^{8} (I_i - \varphi) \Delta t$, $6.5 = \sum_{1}^{8} I_i \Delta t - \varphi (8 \times \Delta t)$

 $6.5 = [(0.2 \times 2) + (0.60 \times 2) + (0.70 \times 2) + (1.10 \times 2) + (1.07 \times 2) + (0.58 \times 2) + (0.52 \times 2) + (0.52 \times 2)] - 16\varphi$

$$\Phi = (10.58 - 6.5)/16 = 0.255 \text{ cm/h}$$

 M_c = Number of pulses with rainfall intensity $M_c \ge \varphi$

Here, $I_i \ge 0.255$ cm/h is 7, $M_c = 7 \neq M$, hence assumed M is not correct.

Thus, a new value of M = 7 in the next trial.

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Solution Trial 2 Assuming M = 7, $t_e = M \times \Delta t = 14$ hours Pulse 1 is omitted. Runoff, $R_d = \sum_1^7 (l_i - \varphi) \Delta t$, $6.5 = \sum_1^7 l_i \Delta t - \varphi(7 \times \Delta t)$ $6.5 = \left[\begin{pmatrix} 0.60 \times 2 \end{pmatrix} + (0.70 \times 2) + (1.10 \times 2) + (1.07 \times 2) \\ + (0.58 \times 2) + (0.52 \times 2) + (0.52 \times 2) \\ - (0.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) \\ - (1.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) \\ - (1.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) \\ - (1.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) + (0.52 \times 2) \\ - (1.52 \times 2) + (0.52 \times 2) + (0.52$

Trial 2

Assuming M = 7, $te = M \times \Delta t = 14$

Pulse 1 is omitted.

Runoff, $R_d = \sum_{1}^{7} (I_i - \varphi) \Delta t$, $6.5 = \sum_{1}^{7} I_i \Delta t - \varphi(7 \times \Delta t)$

 $6.5 = \left[(0.60 \times 2) + (0.70 \times 2) + (1.10 \times 2) + (1.07 \times 2) + (0.58 \times 2) + (0.52 \times 2) + (0.52 \times 2) \right] - 14\varphi$

 $\varphi = (10.18 - 6.5)/14 = 0.26 \text{ cm/h}$

 M_c = number of pulses with rainfall intensity $M_c \ge \varphi$

Here, $I_i \ge 0.26$ cm/h is 7, $M_c=7=M$ (correct)

The φ -index of the storm is 0.26 cm/h and the duration of rainfall excess, t_e is 14 hours.

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Fig.3 shows the Hyetograph and Rainfall Excess of the storm- Example 16.1

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W-Index			
The initial loss and the average	es are separated from the total abstraction value of infiltration rate is called W-inde	ons for refining th x.	the φ -index,
• Thus, W-index	is the average rate of infiltration after sep-	arating the initial	loss.
• It is expressed a	IS:		
	$W = \frac{P - R - I_a}{t_e}$		
	P = Total precipitation		
	R = Total storm runoff		
	$I_a = \text{Initial losses}^{\bullet}$		
	t_e = Duration of the rainfall excess		
Surface Water Hydrology: M02L16	Dr. Rajib Maity, IIT Kharagpur	14	

W-Index

The initial losses are separated from the total abstractions for refining the φ -index, and the average value of infiltration rate is called W-index. Thus, W-index is the average rate of infiltration after separating the initial loss.

$$W = \frac{P - R - I_a}{t_e}$$

Where, P = Total precipitation

R = Total storm runoff

 I_a = Initial losses

 t_e = Duration of the rainfall excess

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Procedure for Estimation of W-Index

- 1. Deduct the initial loss, I_a from the storm hyetograph, and use the resulting hyetograph.
- 2. Assume that out of given N pulses, M number of pulses have rainfall excess

(Note: $M \leq N$). Select M number of pulses in decreasing order of rainfall intensity, I_i .

- 3. Find the value of W, that satisfies the relation $R_d = \sum_{1}^{M} (I_i W) \Delta t$
- 4. Using *W* from Step 2, find the number of pulses (M_c), which give rainfall excess. (M_c = number of pulses with rainfall intensity $I_i \ge W$)
- 5. If $M_c = M$, then W of Step 2 is the correct value of W-index. If not, repeat the procedure from Step 1 onwards with the new value of M.

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ample 10.2							
n a 210 minutes duration	storn	n given	rainfal	l intensit	ies are ob	served in	successiv
0 minutes intervals. Ass	uming	, the φ	-index	value as	3 mm/h a	nd an ini	tial loss of
.8 mm, determine the tot	al rain	fall, ne	t runof	f and W-i	ndex for t	he storm.	
	11						
Time interval (minutes)	0-30	30-60	60-90	90-120	120-150	150-180	180-210
Dainfall interaiter (man /h)	6	6	10	12	2	2	12
Rainiali intensity (mm/n)	0	0	18	15	2	4	12
Raman mensity (mm/n)	0	0	18	13	2	2	12
Raman mensity (mm/h)	0	0	18	•	2	2	12

Example 16.2

In 210 minutes, duration storm given rainfall intensities is observed in successive 30 minutes intervals. Assuming the φ -index value as 3 mm/h and an initial loss of 0.8 mm, determine the total rainfall, net runoff, and W-index for the storm.

Time interval (minutes)	0-30	30-60	60-90	90-120	120-150	150-180	180-210
Rainfall intensity (mm/h)	6	6	18	13	2	2	12

(Refer Slide Time: 16:03)

C1			φ-muex - 5 mm/n,	mitiai 1055 – 0.8 mi	m
Intration	$loss = \varphi$	$\Delta t = 3 \times 0.$	5 = 1.5 mm		
Evalu	ation of t	he rainfall hy	retograph	Incremental rainfall	- Infiltration los
Pulse No.	Time interval (min)	Intensity of rainfall, l _i (mm/h)	Incremental Rainfall (mm) (<i>l_imm/h</i> × 0.5 h)	Runoff (mm)	
1	0-30	6	3.0	1.5	
2	30-60	6	3.0	1.5	
3	60-90	18	9.0	7.5	
4	90-120	13	6.5	5.0	
5	120-150	2	1.0	0	
6	150-180	2	1.0	0	
7	180-210	12	6.0	4.5	

Solution

Given, $\Delta t=30$ minutes = 0.5 h, φ -index = 3 mm/h, Initial loss = 0.8 mm

Infiltration loss = φ . Δt =3×0.5=1.5 mm

Pulse No.	Time interval (min)	Intensity of rainfall, I _i (mm/h)	Incremental Rainfall (mm) (<i>l_i</i> mm/h × 0.5 h)	Runoff (mm)
1	0-30	6	3.0	1.5
2	30-60	6	3.0	1.5
3	60-90	18	9.0	7.5
4	90-120	13	6.5	5.0
5	120-150	2	1.0	0
6	150-180	2	1.0	0
7	180-210	12	6.0	4.5
			Total= 29.5 mm	Total= 20 mm

(Refer Slide Time: 17:37)



In fig.4 you see that difference in this plot that the initial first part, the initial loss is designated here and this phi index is given as a 3 mm per hour.



Fig.4 shows the Hyetograph and Rainfall Excess of the storm- Example 16.2

(Refer Slide Time: 17:48)



Calculation of W-index

Deduct initial loss from the rainfall hyetograph.

For the first pulse,

Incremental rainfall = 3 - 0.8 = 2.2 mm

Pulse No.	Time (h)	Incremental Rainfall (mm)	Rainfall intensity (mm/h) for <i>W</i> -index computation
1	0.5	2.2	4.4
2	1	3.0	6
3	1.5	9.0	18
4	2	6.5	13
5	2.5	1.0	2
6	3	1.0	2
7	3.5	6.0	12



Fig5. Shows the rainfall hyetograph after deducting the initial loss

(Refer Slide Time: 18:29)

Calculation of W-index			
Trial 1			
Assuming $M = 5$, $t_e = M \times \Delta$	$t = 5 \times 0.5 = 2.5$ hours		
Select pulses from decreasing	g order of rainfall intensity. Puls	se 5 and 6 are omit	ited.
Runoff, $R_d = \sum_{1}^{5} (I_i - W) \Delta t$,	$20 = \sum_{1}^{5} I_{i} \Delta t - W (5 \times \Delta t)$	t)	
$20 = [(4.4 \times 0.5) +$	$(6 \times 0.5) + (18 \times 0.5) + (13$	× 0.5) +	
($[12 \times 0.5)] - 2.5W$		
$W = \frac{26.70 - 20}{2.5} = 2.68$	3 mm/h		
M_c = number of pulses with n	rainfall intensity $M_c \ge W$		_
Here, $I_i \ge 2.68 \text{ mm/h}$ is 5, M	$M_c = 5 = M$, hence assumed M	is correct.	
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Calculation of W-index

<u>Trial 1</u>

Assuming M=5, $t_e=M \times \Delta t = 5 \times 0.5 = 2.5$ hours

Select pulses from decreasing order of rainfall intensity. Pulse 5 and 6 are omitted.

Runoff, $R_d = \sum_{i=1}^{5} (I_i - W) \Delta t$, $20 = \sum_{i=1}^{5} I_i \Delta t - W(5 \times \Delta t)$

 $20 = [(4.4 \times 0.5) + (6 \times 0.5) + (18 \times 0.5) + (13 \times 0.5) + (12 \times 0.5)] - 2.5W$

W= (26.70–20)/2.5=2.68 mm/h

 M_c = number of pulses with rainfall intensity $M_c \ge W$

Here, $I_i \ge 2$. 68 mm/h is 5, $M_c=5=M$, hence assumed M is correct.

(Refer Slide Time: 20:04)

	Areal extent of sub		R	Rainfall (cm)		
Sub- area	area as % of catchment	φ-index	First 2 hour	Second 2 hour	Third 2 hour	
Р	35 %	0.25	0.82	1.50	1.10	
Q	40 %	0.45	0.95	1.30	1.0	
R	25 %	0.30	0.85	1.20	0.90	

Example 16.3

Details related to an isolated 6-hour storm that occurred over a catchment are given. Estimate the runoff from the catchment due to the storm.

	American terreterit		Rainfall (cm)			
Sub- area	Areal extent of sub- area as % of catchment	φ-index	First 2 hour	Second 2 hour	Third 2 hour	
Р	35 %	0.25	0.82	1.50	1.10	
Q	40 %	0.45	0.95	1.30	1.0	
R	25 %	0.30	0.85	1.20	0.90	

(Refer Slide Time: 21:14)

ub- irea	Proportion of areal extent of total catchment	φ−inde x	Rainfall (cm)	Duration (h)	Rainfall intensity (cm/h)	Intensity of rainfall excess (cm/h)	Depth of rainfall excess (cm)	Runoff depth in sub-area (cm)	Runoff contribution the total catchment area (cm)
			0.82	2	0.41	0.16	0.32		0.67
Р	0.35	0.25	1.50	2	0.75	0.50	1.00	1.92	
			1.10	2	0.55	0.30	0.60		
		0.45	0.95	2	0.47	0.02	0.04	0.54	0.21
Q	0.40		1.30	2	0.65	0.20	0.40		
			1.0	2	0.50	0.05	0.10		
			0.85	2	0.42	0.12	0.24		
R	0.25	0.25 0.30	1.20	2	0.60	0.30	0.60	1.14	0.28
			0.90	2	0.45	0.15	0.30		
									Total=1.16

Sub- area	Proportion of areal extent of total catchment	φ−inde x	Rainfall (cm)	Duration (h)	Rainfall intensity (cm/h)	Intensity of rainfall excess (cm/h)	Depth of rainfall excess (cm)	Runoff depth in sub-area (cm)	Runoff contribution to the total catchment area (cm)	
			0.82	2	0.41	0.16	0.32			
Р	0.35	Solution 0.25	1.50	2	0.75	0.50	1.00	1.92	0.67	
			1.10	2	0.55	0.30	0.60			
	0.40		0.95	2	0.47	0.02	0.04			
Q		0.45	1.30	2	0.65	0.20	0.40	0.54	0.21	
			1.0	2	0.50	0.05	0.10			
	R 0.25			0.85	2	0.42	0.12	0.24		
R		0.25 0.30	1.20	2	0.60	0.30	0.60	1.14	0.28	
			0.90	2	0.45	0.15	0.30			
									Total=1.16 cm	

Solution

The total runoff from the catchment due to the storm is 1.16 cm.

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Practical Use of Infiltration Indices

- > The φ -index for a catchment, during a storm, in general, depends upon the soil type, vegetation cover, initial soil moisture condition, storm duration, and intensity. To obtain complete information on the interrelationship between these factors, a detailed extensive study of the catchment is necessary.
- > Therefore, to use the infiltration index for the estimation of flood magnitudes corresponding to critical storms, a simplified relationship for φ -index is adopted.
- The initial losses are assumed to be negligible in the case of φ-index but considered in the case of W-index.
- > Further, only the soil type and rainfall are found to be critical in the estimate of the φ -index for maximum flood-producing storms.

(Refer Slide Time: 24:04)

Summary		
 Infiltration index r Two infiltration in namely, <i>φ</i>-index a 	epresents a constant average rate o ndices are commonly used in 1 nd W-index.	f infiltration. hydrologic analysis,
 φ-index is the aver equal to the runoff 	rage rainfall value above which th volume.	ne rainfall volume is
• <i>W</i> -index is the ref and depression sto	ned form of the φ -index by includ rage loss, i.e., initial loss.	ding the interception
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Summary

In summary, we learned the following points from this lecture:

- > The infiltration index represents a constant average rate of infiltration.
- > Two infiltration indices are commonly used in the hydrologic analysis, namely, φ -index and W-index.
- > φ -index is the average rainfall value above which the rainfall volume is equal to the runoff volume.
- > W-index is the refined form of the φ -index by including the interception and depression storage loss, i.e., initial loss.