Florida Department of Environmental Protection

Hydrology – 4a: Runoff and Flow Hydrographs

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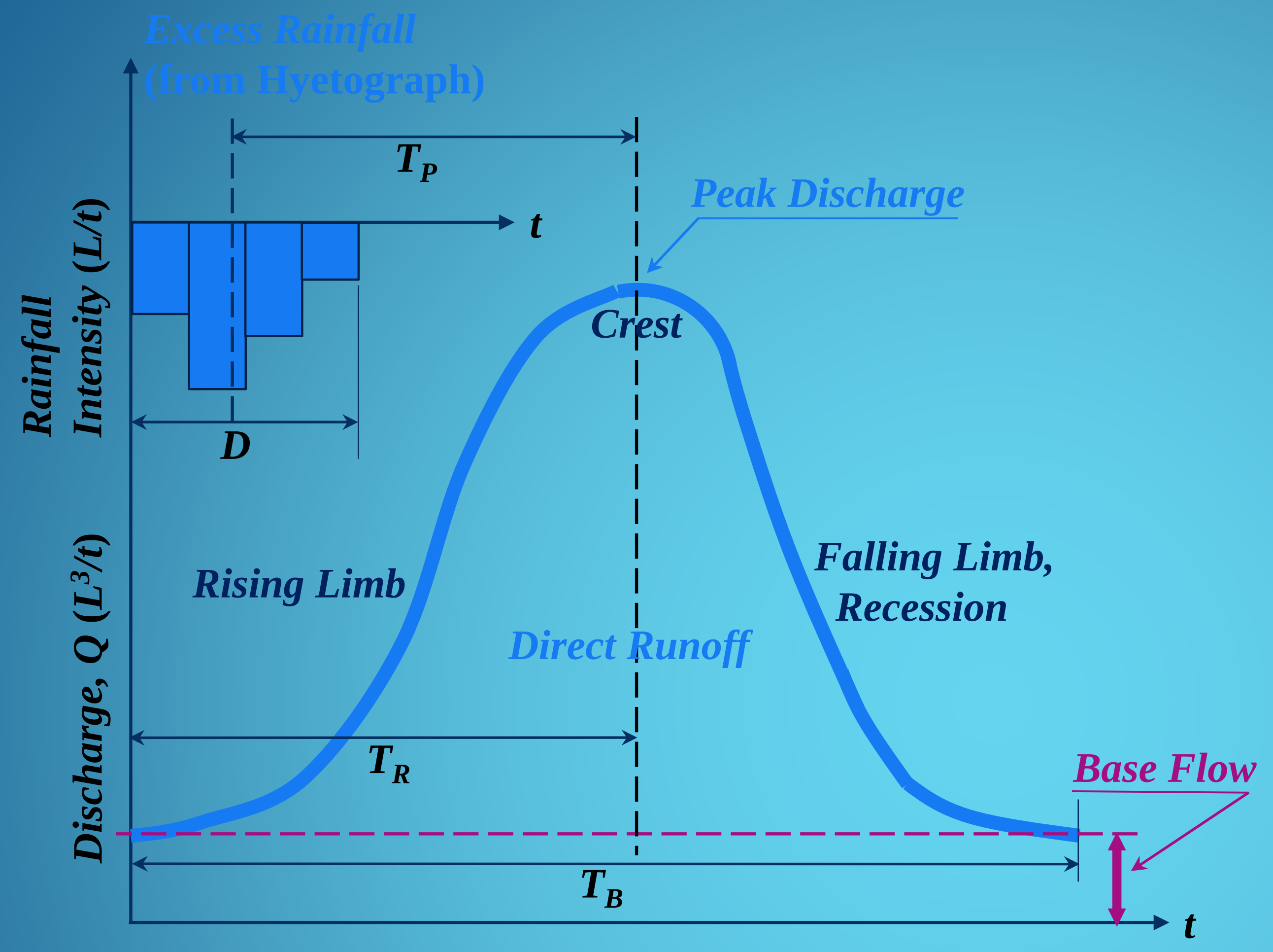
- ***Runoff*** is the amount of flow generated from precipitation after subtracting the losses (i.e., hydrologic abstractions)
- It is perhaps the most important component of the Hydrologic Cycle to evaluate when dealing with many water resources projects
- Runoff begins as soon as the water from rainfall which reaches the ground surface and is retained temporarily as detention storage acquires sufficient energy to start moving initially as ***overland flow***
- Overland flow or "sheet flow" converges to more continuous well-defined small streams or channels that constitute the conveyance system for ***streamflow***
- The volume of runoff is primarily evaluated from the ***excess rainfall*** (e.g., rainfall – hydrologic abstraction) times the watershed area

Runoff

Runoff Hydrograph

- A ***Runoff Hydrograph*** is a plotted representation of discharge versus time
- The integration of the runoff hydrograph (direct runoff) matches the volume of water obtained from the excess rainfall (hyetograph) multiplied by the watershed area
- For a typical single-storm event, a hydrograph consists of a rising limb and a falling limb (or recession), and between the limbs there is the crest containing the peak which represents the maximum discharge associated with the specific storm event
- Timing parameters have to be defined for predicting runoff



Runoff Hydrograph

T_P is the *Time to Peak* and is the time interval from the centroid of the Excess Rainfall to the peak (max discharge) of the Hydrograph

D is the *Duration* of the Excess Rainfall

T_R is the *Time to Rise* and is the length of time between the beginning of the Excess Rainfall and the peak of the Hydrograph

T_B is the *Time of Base* or the duration of the Hydrograph produced by Direct Runoff (i.e., only streamflow or without taking into account the *Base Flow*)

Base Flow is a certain amount of normal or day-to-day flow that occurs in the channel of a watershed during most of the year and typically comes from groundwater

- The discharge of a watershed is a time rate of volume (L^3/T) and its measurements define the hydrograph. Stream discharge can be measured by several methods
  - **Velocity-Area Methods**
  - **Weirs** and **Flumes**
  - **Dilution Method**
- The ***Velocity-Area Method*** consists in determining the mean flow velocity through a predetermined cross sectional area which is normal to such flow velocity. With the advance in technology this streamgauging method can use a wide variety of devices

Measurements of Discharge

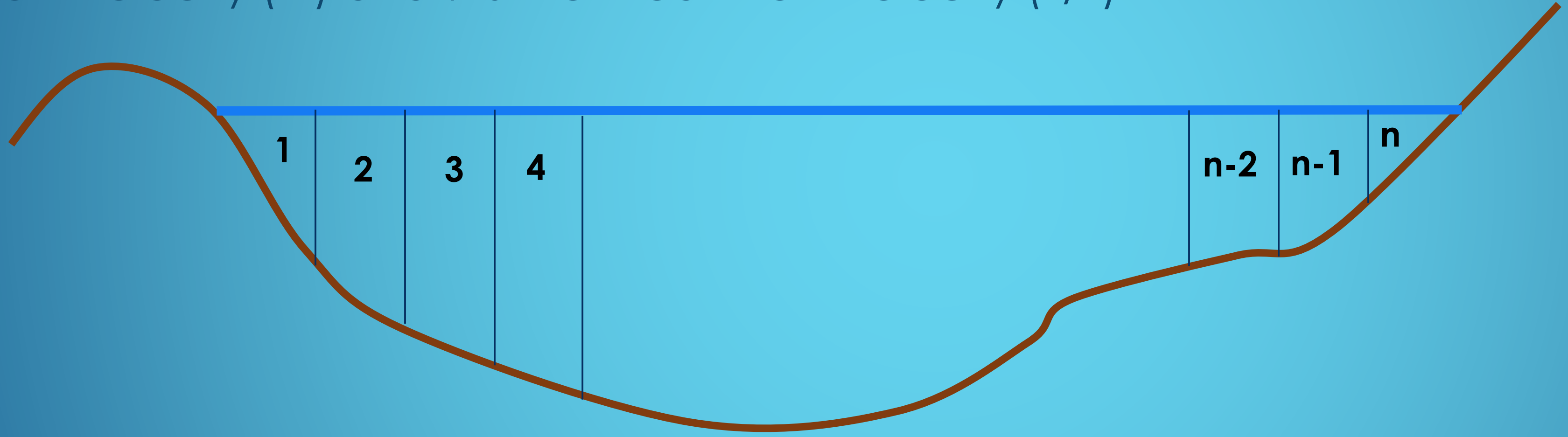
Measurements of Discharge

- The method is based on the Continuity Equation that derives from the principle of Conservation of Mass

$$\boxed{Q = A \times \overline{v} \;\ldots\; [4.1]}$$

where $\boldsymbol{Q}$ is the flow discharge (L^3/T), $\boldsymbol{A}$ is the cross sectional area normal to the flow velocity (L^2) and $\overline{\boldsymbol{v}}$ is the mean flow velocity (L/T)

$$\boxed{Q = \sum_{i=1}^{n} A_i \times \bar{v}_i \;\ldots\; [4.2]}$$



- ***Electromagnetic Flowmeters*** work on the principle of electromagnetic induction. They apply a magnetic field to the metering tube, which results in a differential pressure proportional to the flow velocity

Table 4.1 Point Velocity Measurements for Streamgauging (USGS)

Type	Water Depth, *D* (ft)	Point Location (from surface)	Mean Velocity ($\bar{v}$)
Single point	1 – 2	0.6 *D*	$v_{0.6}$
Two-point	2 – 10	0.2 & 0.8 *D*	$\frac{1}{2}(v_{0.2}+v_{0.8})$
Three-point	10 – 20	0.2, 0.6 & 0.8 *D*	$\frac{1}{4}(v_{0.2}+2v_{0.6}+v_{0.8})$
Five-point	> 20	*S*, 0.2, 0.6, 0.8 & *B*	* $1/10\,(v_S+3v_{0.2}+2v_{0.6}+3v_{0.8}+v_B)$

* v_S is measured one-foot below the surface and v_B one-foot above the bottom of stream

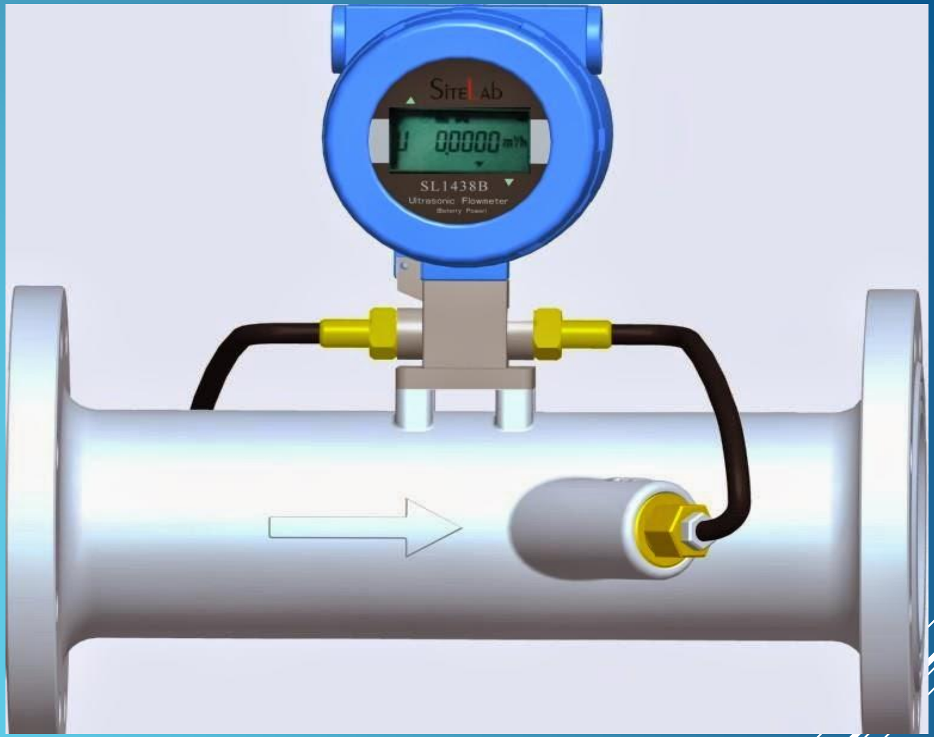
Measurements of Discharge

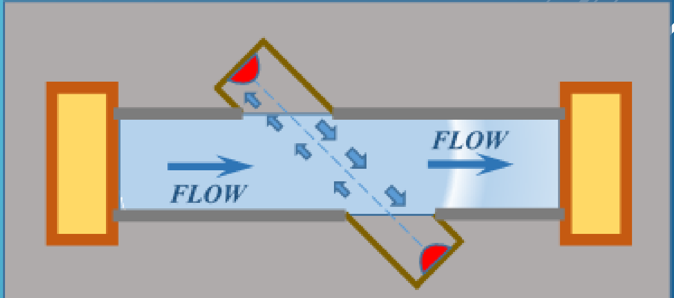
- ***Acoustic Doppler Current Profiler (ADCP)*** is a hydroacoustic flow velocity meter which transmits and receives sound signals from piezoelectric oscillators. Its operation is similar to that from a sonar; the travelling time of sound waves gives an estimate of the distance used to compute the velocity of the flow. ***ADCPs*** are accurate devices and due to bottom tracking (sound waves bouncing off the bottom), they can be used to autonomously and remotely navigate underwater vehicles. ***ADCPs*** use in the ocean is a concern due to the interference of the acoustic signals with cetacean navigation and changes in their environment location

Measurements of Discharge

Measurements of Discharge

- ***Ultrasonic Velocity Meter (UVM)*** is a device to measure continuous flow velocities in streams or conduits at time intervals as low as 15 minutes. A ***UVM*** has one or more paths of sensor transducers (transmitter /receiver). Transmitters send pulsating ultrasonic waves in a predefined frequency to the receivers on the opposite side. The difference in frequency is proportional to the average flow velocity. The more paths (multi-beam *UVM*) are used, the higher the achieved accuracy is. Accuracy for a single-beam *UVM* is about 1% of the flow discharge.





Ultrasonic waves are sent and received between transducers. As flow increases, waves traveling upstream slow down

Measurements of Discharge

- ***Weirs*** and ***Flumes*** are measurement devices widely used to estimate flow discharges in streams and channels. They constrict the flow of water and it passes over the crest at the critical depth. Critical depth occurs at minimum specific energy and from their mathematical relationship, the flow discharge can be obtained

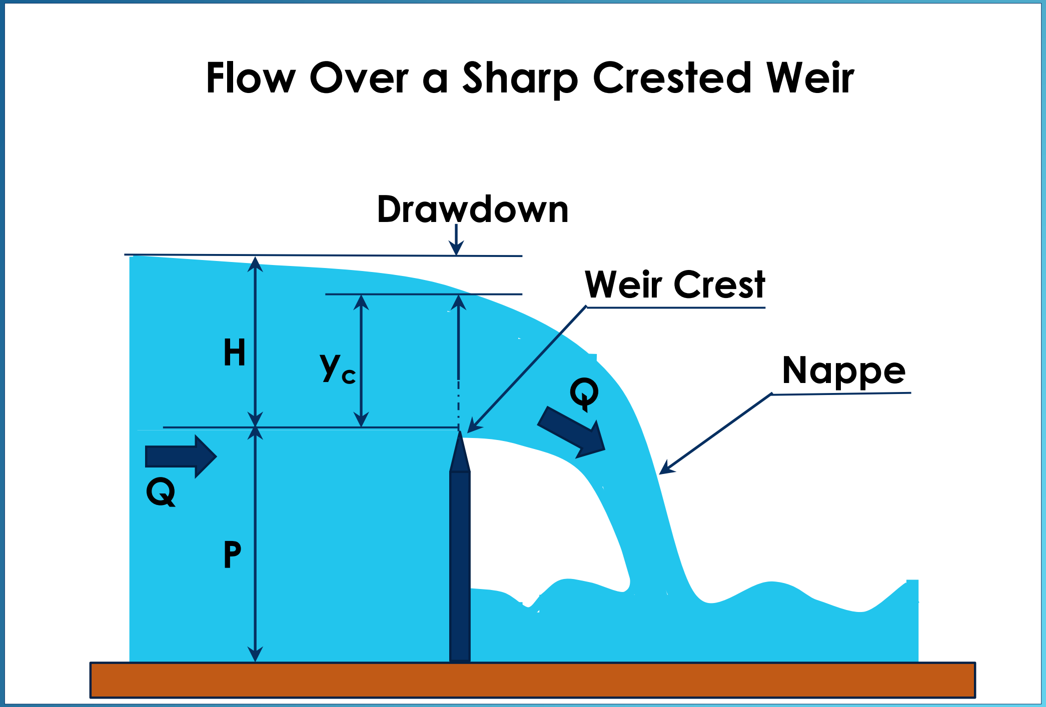
Typical V-Notch Weir installed in a concrete-lined trapezoidal channel

Metal plate Rectangular Weir installed in an earthen channel

Concrete Long-throated Flume being built in a large capacity stream. Critical depth develops on the broad-crested weir section

Pre-built metal Parshall Flume installed in a medium size canal

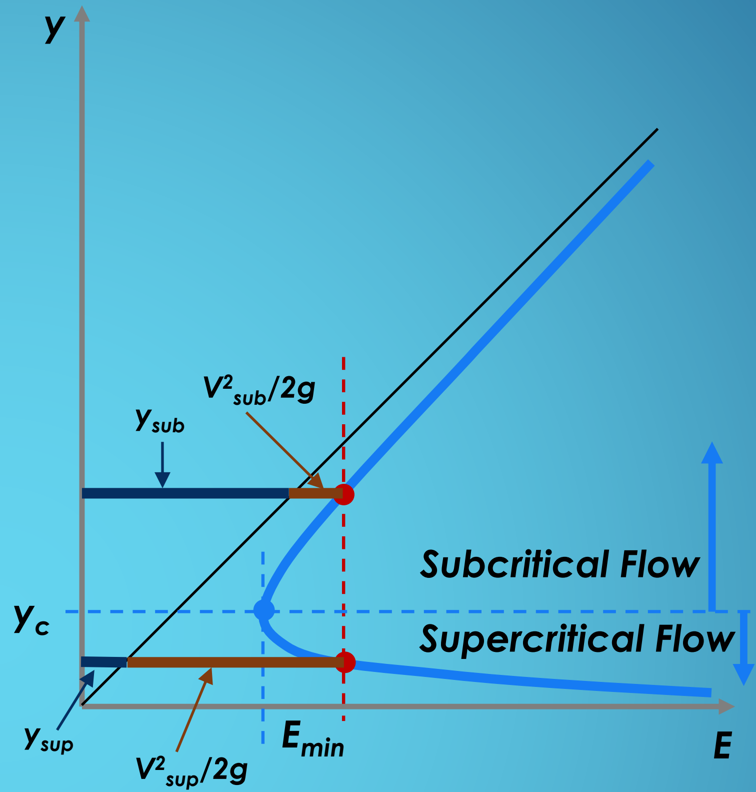
Measurements of Discharge

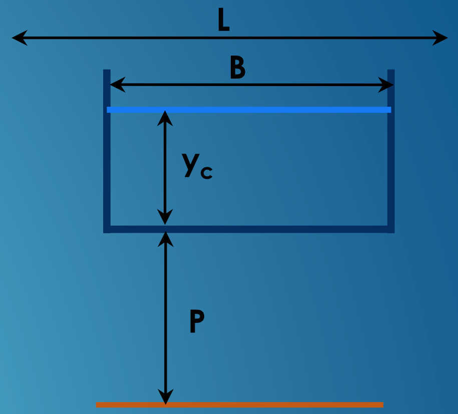


$$Q = 3.33 \times \left((B - 0.2 \times H)\left(H^{3/2}\right) \right) \ldots \quad [4.3]$$

a) $L - B \geq 4H_{MAX}$; b) $P \geq 2H_{MAX}$; and c) $H/B \leq 0.33$

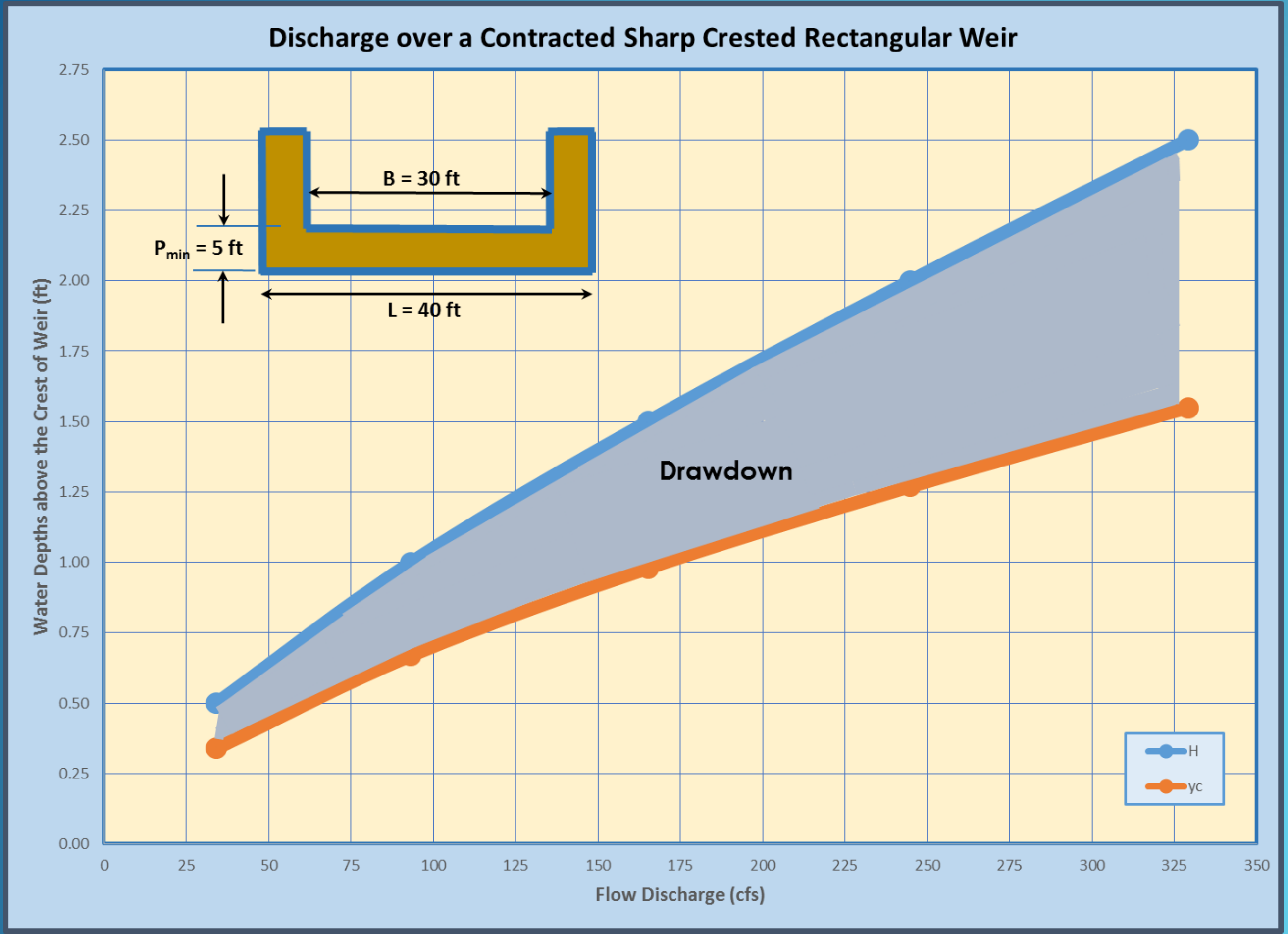
Specific Energy, $E = y + \alpha\, v^2/2g$





$$y_c = \sqrt[3]{\frac{Q^2}{B^2 \times g}} \ldots [4.3]$$

Measurements of Discharge



$$Q = 3.33 \times \left((B - 0.2 \times H)(H^{3/2}) \right) \ldots \quad [4.4]$$

a) $L - B \geq 4H_{MAX}$; b) $P \geq 2H_{MAX}$; and c) $H/B \leq 0.33$

$$y_c = \sqrt[3]{\frac{Q^2}{B^2 \times g}} \ldots [4.3]$$

Measurements of Discharge

- The ***Dilution Method*** of measuring the discharge of a stream is used in cases where other conventional methods cannot be used
- A known amount of a tracer is introduced into the stream. Samples are collected at a downstream site and are analyzed using a fluorometer
- The discharge is determined over a length of the stream in relation to the experiment setup, rather than at a single point
- Tracers or dyes (e.g., radioactive Na_{24}, common salt, SF_6 and different types of Rhodamine) have to be stable, harmless to the biotic community, chemically inert, detectable in low concentration and relatively inexpensive

Measurements of Discharge

- The discharge of a stream when the tracer is continuously injected is computed as follows:

$$Q = q \times \frac{C}{c} \ldots [4.5]$$

where q is the rate of injection, C is the concentration of the injection tracer solution and c is the diluted concentration at the downstream station (*ppb*)

- When the tracer is instantaneously injected, the discharge is,

$$Q = \int_0^\infty \frac{C \times V}{c} dt \ldots [4.6]$$

where V is the volume of injected solution

Measurements of Discharge

- **PROBLEM 1**: At 7:00 am 20 Kg of a tracer is dumped into the stream and sampling started one hour later at two sites located 8 miles and 16 miles downstream, obtaining the concentrations in the following table

Time	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
C (*ppb*) – 1^{st} Site	Inj	0	2	6	12	8	7	3	1	0	0	0	0	0
C (*ppb*) – 2^{nd} Site	Inj	0	0	0	1	6	8	6	5	3	3	2	1	0

Compute:
a) Average discharge for the 1^{st} reach (Injection to 1^{st} Site: 8-mile)
b) Average discharge for the 2^{nd} reach (1^{st} Site to 2^{nd} Site: 8-mile)
c) What percent of the dye was lost between the two collection sites?
d) What is the mean velocity of the dye cloud (plume)?

Dilution Method Problems

Computation of Stream Discharge (Instantaneous Injection)

Hour	t (hr)	Δt (hr)	1st Collection Site @ 8 mile c (ppb)	c Δt (ppb –hr)	c t (ppb –hr)	2nd Collection Site @ 16 mile c (ppb)	c Δt (ppb –hr)	c t (ppb –hr)
7	0	0	Time of Injection			Time of Injection		
8	1	1	0	0	0	0	0	0
9	2	1	2	2	4	0	0	0
10	3	1	6	6	18	0	0	0
11	4	1	12	12	48	1	1	4
12	5	1	8	8	40	6	6	30
13	6	1	7	7	42	8	8	48
14	7	1	3	3	21	6	6	42
15	8	1	1	1	8	5	5	40
16	9	1	0	-	-	3	3	27
17	10	1	0	-	-	3	3	30
18	11	1	0	-	-	2	2	22
19	12	1	0	-	-	1	1	12
20	13	1	0	-	-	0	-	-
	∑	13	39		181	35		255

Integral Eq. 4.6 can be rewritten in discrete form as follows

$$Q = \frac{C \times V}{(\sum c) \times \Delta t} \ldots [4.7]$$

Note that C x V is the mass of the tracer {ppb x lt = $\mu g/lt$ x lt = μg}

Dilution Method Problems

$$a)\ \ Q=\frac{20\,Kg\times(10^9\ \mu g/Kg)}{39\,\mu g/lt-hr\times(3600\sec/hr)\times(1000\,lt/m^3)}=\frac{20\times10^3\ m^3/\sec}{39\times3.6}=142.5\,m^3/\sec$$

$$b)\ \ Q=\frac{20\,Kg\times(10^9\ \mu g/Kg)}{35\,\mu g/lt-hr\times(3600\sec/hr)\times(1000\,lt/m^3)}=\frac{20\times10^3\ m^3/\sec}{35\times3.6}=158.7\ m^3/\sec$$

$$c)\ \ Loss\ of\ dye=\frac{\sum c_8-\sum c_{16}}{\sum c_8}\times100=\frac{39\ ppb-35\ ppb}{39\ ppb}\times100=10.26\%$$

d) Take moments about t=0 to get the centroid of Time vs. Concentration function

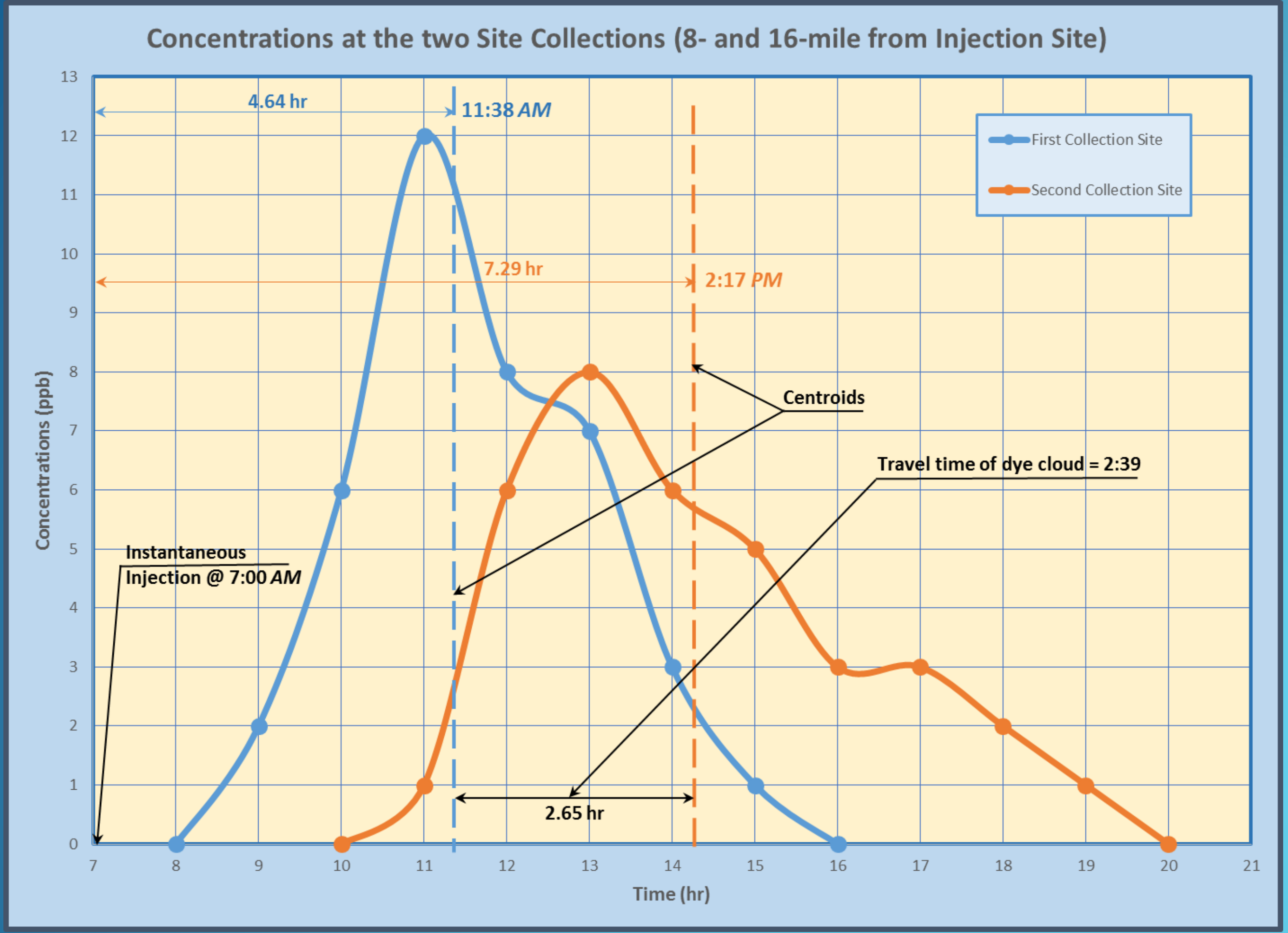
$t_{8m}=\Sigma\,(ct)/\Sigma c=181\ ppb\text{-}hr/39\ ppb=4.64\ hr+7{:}00\ AM=11{:}38\ AM$

$t_{16m}=\Sigma\,(ct)/\Sigma c=255\ ppb\text{-}hr/35\ ppb=7.29\ hr+7{:}00\ AM=2{:}17\ PM$

$Travel\ time\ of\ dye\ cloud=14.29\ hr-11.64\ hr=2.65\ hr$

$Average\ velocity\ of\ dye\ cloud=8\ miles\,/\,2.65\ hr=3.02\ mph$

Dilution Method Problems



Dilution Method Problems

- **PROBLEM 2**: A 20% by weight solution of Rhodamine B tracer was discharged into a stream at a rate of 6 cm^3/sec. The equilibrium concentration of the dye after complete mixing was found to be 3 ppb. Compute the stream discharge

  Eq. 4.5 is used. $C = 20\ parts/100 = 2 \text{ x } 10^8 / [10^9] = 2 \text{ x } 10^8\ ppb$ for a 20% solution by weight

$$Q = q \times \frac{C}{c} = 6\ cm^3/\sec \times \frac{2\times10^8\ ppb}{3\ ppb} = 4\times10^8\ cm^3/\sec = 400\ m^3/\sec \quad [1\ m^3 = 10^6\ cm^3]$$

$$Q = 14{,}124\ ft^3/\sec\ (cfs) \qquad [1 m^3 = 35.31\ ft^3]$$

Dilution Method Problems

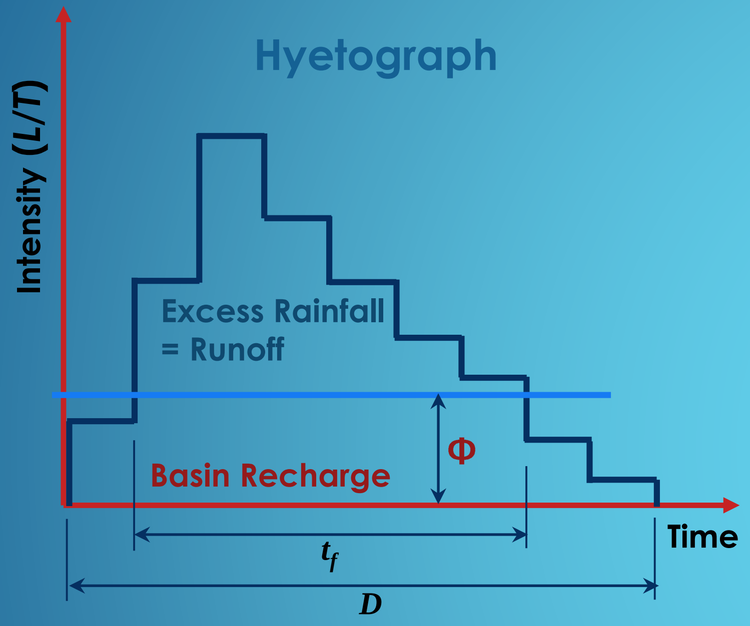
- The **Φ *Index Method*** is an application of a rainfall/runoff event in which the subtraction of the hydrological abstractions (mainly infiltration) is carried out equally over the entire duration of the rainfall
- When a flood hydrograph is measured for a specific rainfall, the **Φ** value represents a constant intensity (*L*/*T*) obtained after subtracting the excess rainfall from the rainfall hyetograph
- The **Φ *Index*** represents the watershed (or basin) recharge, and although is considered a rather simplified measure of the infiltration process, is meaningful for large watersheds

The Φ Index Method

- The **_Φ Index Method_** generally assumes that infiltration occurs at some constant or average rate throughout the storm. This implies an underestimation of the initial rates and on the contrary final rates are overstated. This is more marked when considering isolated storms (i.e., little antecedent moisture effect)
- In conclusion, to determine the **_Φ Index_** for a given storm, the amount of observed runoff is determined from the hydrograph, and subtracting this value from the recorded precipitation, the losses are obtained (i.e., hydrologic abstractions). This is distributed uniformly across the storm pattern

The Φ Index Method

- A graphical representation of the Φ Index is as follows



$$\phi = \frac{\text{Basin Recharge}}{\text{Rainfall Duration}} = \frac{F}{D} \quad ...[4.8]$$

Note that when the rainfall intensity at any time interval is smaller that the **Φ** value computed from Eq. 4.8 at that time interval, it is necessary to recalculate a new **Φ** value to account for the amount of water not being supplied by the rainfall. The following example illustrates this case

The φ Index Method

- **PROBLEM 3**: A 7-hour storm has produced a flood of 683.06×10^6 ft^3 found from its direct runoff hydrograph ***(DR Hydrograph)***. The basin has a surface area of 150 $miles^2$. The recorded hyetograph is shown in the following table with a total rainfall of 6.3 inch. Find the Basin Recharge, F and the ϕ Index of this storm

Time (hr)	10-11	11-12	12-13	13-14	14-15	15-16	16-17
Rainfall Intensity (inch/hr)	0.50	0.80	1.53	1.06	1.25	0.82	0.34

$A = 150 \text{ miles}^2 = 4.182 \times 10^9 \text{ ft}^2$

Excess Rainfall (inch) over the basin = V/A = $[683.06 \times 10^6 / 4.182 \times 10^9] \times 12$ inch/ft
Q = Excess Rainfall = 1.96 inch

F = **Basin Recharge** = $\Sigma P - Q = 6.30 - 1.96 =$ **4.34 inch**

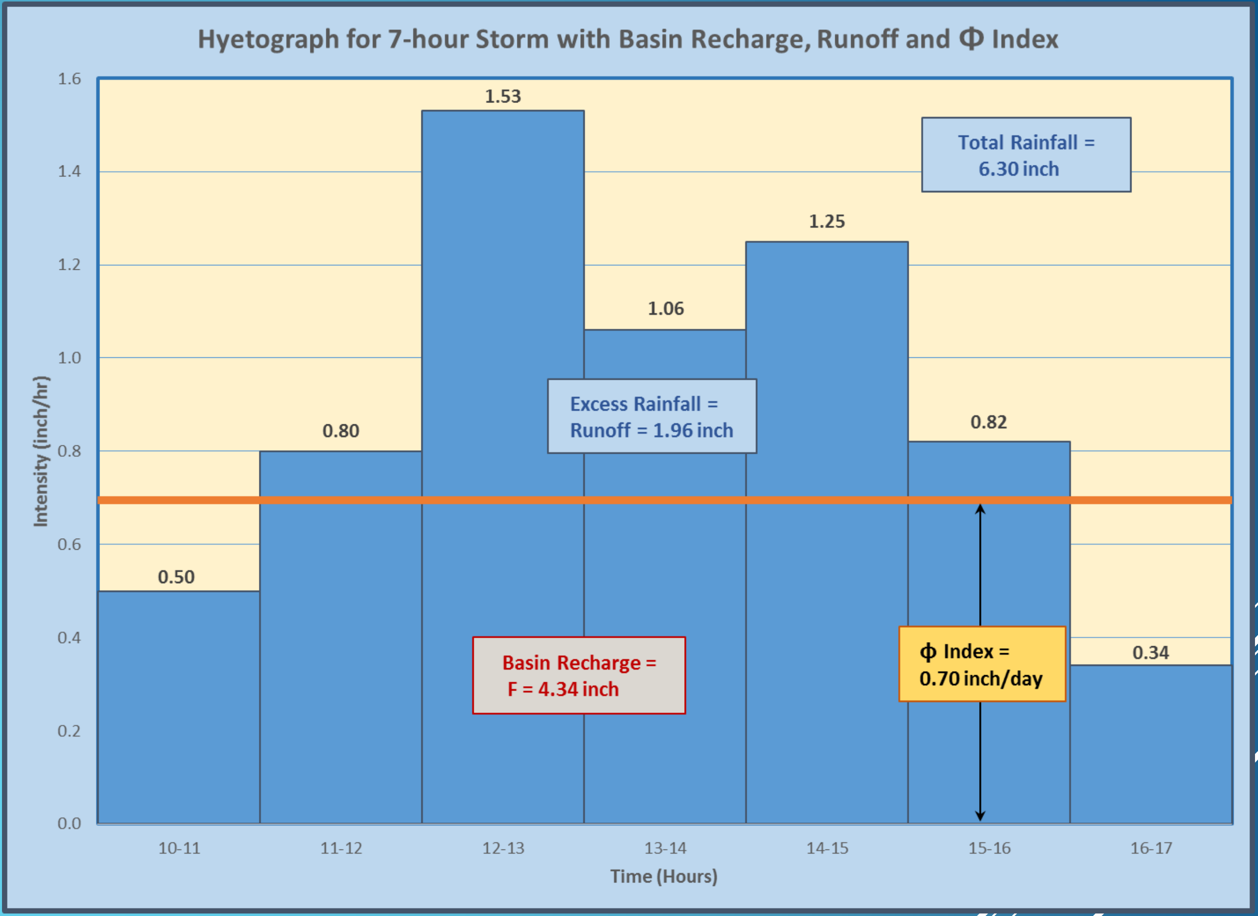
Φ_{init} = 4.34 inch / 7 hr = **0.62 inch/hr**

The Φ Index Method

Note that ϕ_{init} = 0.62 inch/hr is smaller than two values of rainfall intensity for the storm, therefore the storm does not provide sufficient water and a new φ value has to be calculated

Computation of Φ Index for a 7-hour Storm

Time (hr)	Rainfall Inten (inch/hr)	Recharge (inch/hr)	φ (inch/hr)
10-11	0.50	0.50	0.50
11-12	0.80	φ=(4.34-0.84)/5 φ=0.7 inch/hr	0.70
12-13	1.53		0.70
13-14	1.06		0.70
14-15	1.25		0.70
15-16	0.82		0.70
16-17	0.34	0.34	0.34
Σ	6.30	4.34	4.34



The φ Index Method

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Questions?

Thank you!