Engineering Hydrology

110401454

Introduction

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Course Contents

Introduction, watershed and flow:

Definition, hydrologic cycle, water balance, watersheds, statistical methods in hydrology, IDF curves, the rational method and water harvesting.

Hydrologic parameters:

Rainfall, evaporation, infiltration, storage, excess rainfall.

Hydrograph and flow:

Hydrograph component, direct and baseflow, UH, synthetic hydrographs.

Course Contents

Groundwater flow:

Aquifers, Darcy law, flow from confined and unconfined aquifers, water table drop, well influence distance, multiple wells system, groundwater recharge.

Introduction to water resources:

Potential water sources, surface and ground storage, reservoir sizing.

Introduction

What do you observe in the image?

What can the civil engineer do?

Amman Jan 8, 2013. (Source: The Jordan Times Jan 8, 2013).

Introduction

What do you observe in the image?

Amman - Zarqa highway near Ain Ghazal intersection Jan 8, 2013.

Introduction

Hydrological useful statements:

Zarqa town resident said: the rain has stopped 1 hour ago, but the flood continued coming from higher areas. Manholes in the streets were flooded by the heavy rain causing damage to his mini-market. The last time I saw such heavy rain was in the 1970s.

Zarqa city (Source: The Jordan Times 25/11/2012)

Introduction

The word Hydrology came from the Latin combination of Hydro that means water and logy that means science. Compared to the hydrology, the course fluid mechanics studies the physics of fluids (water) like: viscosity, shear stress, buoyancy, pressure and force, momentum conservation, energy conservation, mass conservation, etc...

Compared to the hydrology, the course hydraulics studies the behavior of the water like: flow velocity and depth, specific energy, hydraulic jump, hydraulic sections design, flow in pipes, flow under varying head, etc...

Introduction

In general the hydrology is defined as the water science that studies the water formation (precipitation), the water cycle and balance, the variation in precipitation and flow amounts, the land that receives precipitation, the surface and groundwater flow amounts, distribution of the flow with the time.

Applications of the hydrology in **CE**:

- Storm water sewer design,
- Water harvesting,
- Culvert design.

Introduction

Ancient hydrology in Jordan!

Jawa Dam

From Wikipedia, the free encyclopedia

The **Jawa Dam** is the remains of an ancient masonry gravity dam on Wadi Rajil at Jawa in Mafraq Governorate, Jordan, 58 kilometres (36 mi) north of Azraq. It is the oldest known dam in the world, dating back to 3000 BC. The dam was part of a water supply system that eventually consisted of other smaller dams to support the growing local town of Jawa. Therefore, the term **Jawa Dams** is sometimes used to describe the dams around Jawa. The Jawa Dam, though, is the largest of the dams and withheld the largest reservoir.[1][2][3]

Svend Helms, who directed an excavation of the area in 1970, determined that the Jawa Dam was used to harvest rainwater. After winter precipitation runoff was diverted from Wadi Rajil, it was transferred through a small canal to a depression in the ground that was sealed off with a rock wall. This rock wall was the Jawa Dam; it had a 2-metre (6.6 ft) thick core of tampered clay, ash and soil. The core was surrounded with basalt stone walls. Loam and soil were placed at the downstream side of the dam to strengthen it and an impervious blanket was placed on the upstream heel to prevent leaks. On top of this blanket, pervious rock-fill was placed to help release water and drain the reservoir.[1][4] The dam was later heightened by 1–2 metres (3.3–6.6 ft) and its core expanded at the same time to 7 metres (23 ft) thick to further strengthen it.[2]

Over time, other dams, weirs and small canals were built in Jawa to expand the system and increase the water supply. Weirs eventually diverted water into a system of ten reservoirs for farming, herding and human consumption. The Jawa Dam's reservoir held half of the system's combined water storage capacity. The town of Jawa was estimated to quickly reach a size of 2,000 before it collapsed.[2]

Introduction

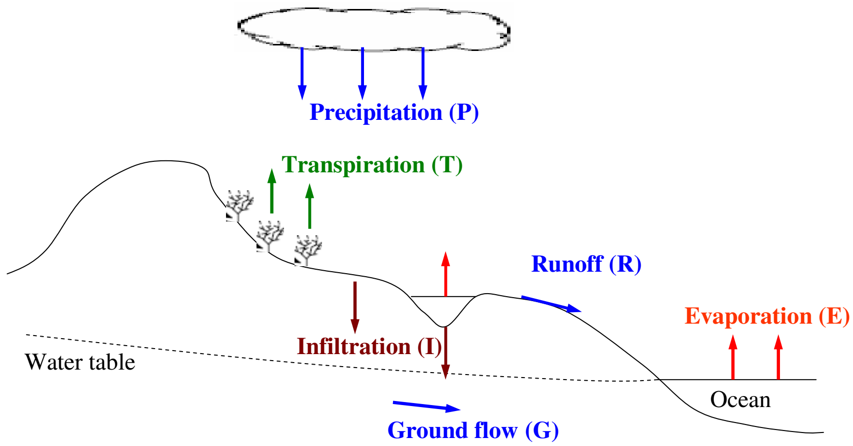
Jawa Dam

Location of Jawa Dam

Location	Jawa, Mafraq Governorate, Jordan
Coordinates	32°20′06″N 37°00′12″E
Construction began	~3000 BC
Dam and spillways	
Type of dam	Gravity, masonry
Height	4.5 m (15 ft)
Length	80 m (260 ft)
Base width	4.5–5 m (15–16 ft)
Impounds	Wadi Rajil
Reservoir	
Creates	Jawa Reservoir
Capacity	31,000 m^3 (1,100,000 cu ft) est.

Hydrologic cycle

The hydrologic cycle represents the water cycle and mass balance of water amounts over a specified region or the whole earth.

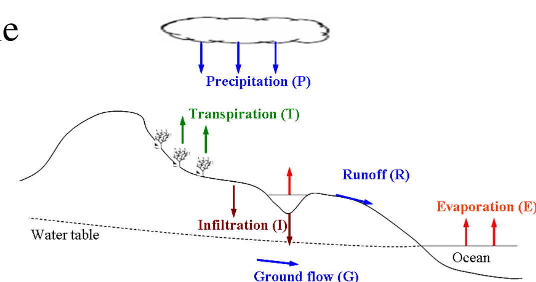


Hydrologic cycle

Water is distributed in the hydrologic cycle as follows: 97.5% as seawater and 2.5% as freshwater (including glaciers and ice caps).

Components of the cycle

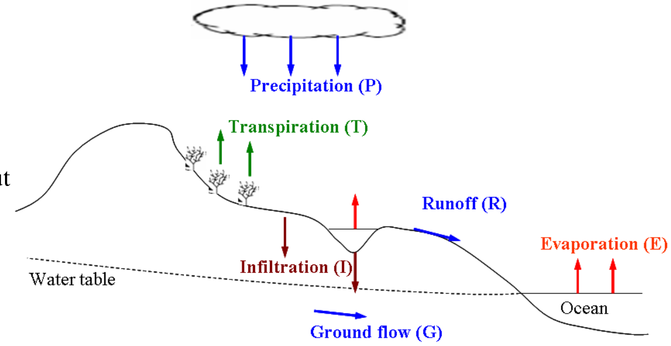
- Precipitation (P),
- Evaporation (E),
- Transpiration (T),
- Infiltration (I),
- Surface runoff (R), and
- Groundwater flow (G)



Hydrologic cycle

For given water system, the mass balance of water volumes over time controls the change in the storage (ΔS):

$$\Delta S = V_{in} - V_{out}$$



V_{in}: total water volume inters the system

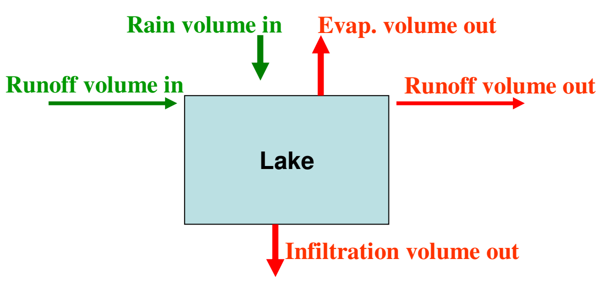
V_{out}: total water volume leaves the system

Hydrologic cycle

Ex: water balance application

A dam of 40km^2 lake receives average water flow of 0.56m^3/s for January while delivers 0.48m^3/s as outflow. The cumulative precipitation for January is 45mm. The cumulative evaporation from the lake surface is 125mm and the cumulative infiltration from the lake bottom is 25mm. Calculate the change in the lake water level during January?

Soln:



Hydrologic cycle

Volume in:

$V_{R\text{-}in} = 0.56 \times 60 \times 60 \times 24 \times 31 = 1{,}499{,}904 m^3$

$V_P = 0.045 \times 40{,}000{,}000 = 1{,}800{,}000 m^3$

Volume out:

$V_{R\text{-}out} = 0.48 \times 60 \times 60 \times 24 \times 31 = 1{,}285{,}632 m^3$

$V_E = 0.125 \times 40{,}000{,}000 = 5{,}000{,}000 m^3$

$V_I = 0.025 \times 40{,}000{,}000 = 1{,}000{,}000 m^3$

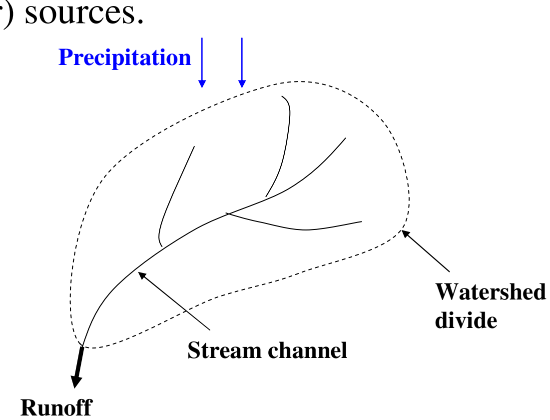
$$\Delta S = V_{in} - V_{out}$$
$$= (1{,}499{,}904+1{,}800{,}000) - (1{,}285{,}632+5{,}000{,}000+1{,}000{,}000)$$
$$= - 3{,}985{,}728 m^3$$

The change in the lake water level is a drop =

= 3,985,728 / 40,000,000 = 0.1m = 10cm.

Watershed definition

The watershed is defined as the land area that contributes surface flow. The catchment is the land area that receives precipitation. The basin is usually large and contributes flow from surface and subsurface (groundwater) sources.



Watershed delineation

Watershed delineation means to mark the watershed boundaries where surface runoff from precipitation will occur.

Rules:

1- Locate the major stream,

2- Mark the peaks of surrounding hilltops

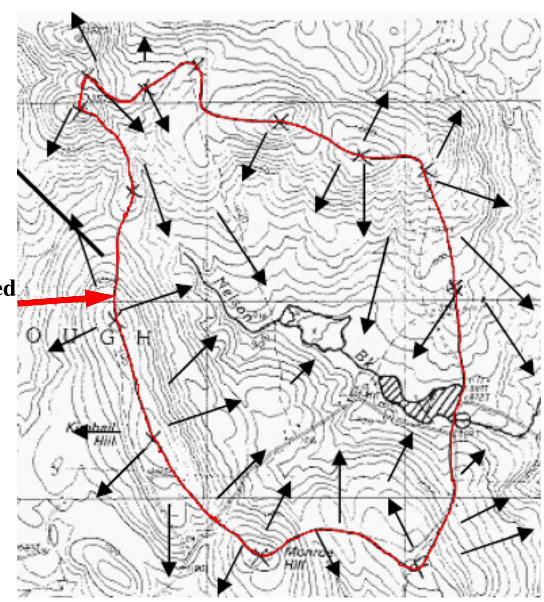
3- Mark flow directions from peaks of hilltops to cross contour lines at right angle.

4- Connect the marks at peaks to include the flow direction arrows towards the major stream.

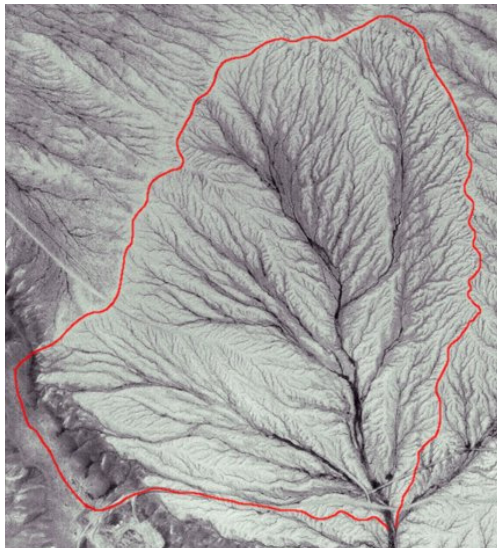
Watershed delineation

Example:

The resulted watershed



Watershed delineation using GIS



Watershed characteristics

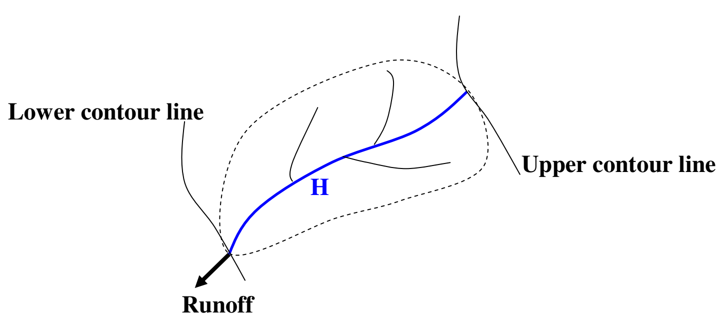
Watershed slope:

The watershed slope can be estimated from topographic maps as follows

$$S = \Delta E/H$$

ΔE : elevation difference along the main stream channel,

H : main stream length, map projected distance.



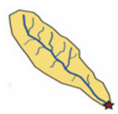
Watershed characteristics

Watershed shape:

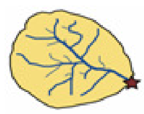
The watershed shape highly affects the flow amount (m^3/s) and the time needed to reach the peak flow. The watershed shape is a result of the watershed slope.

In general, two types of watershed shapes are recognized:

1- Elongated watersheds: results from steep slopes.

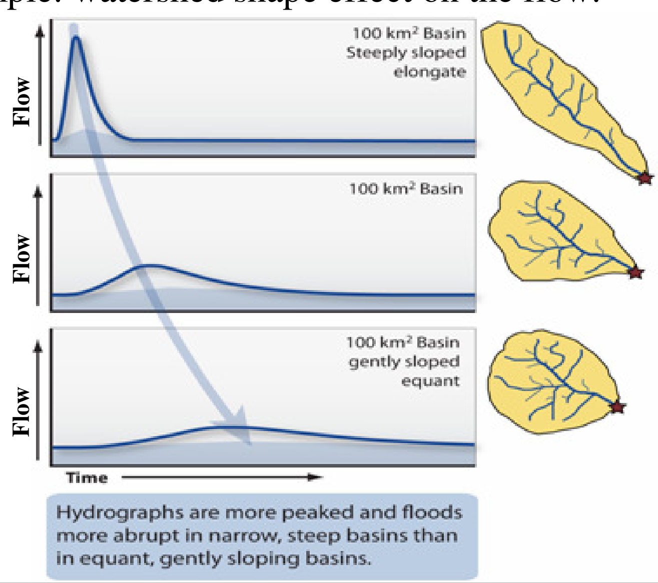


2- Equant watersheds: results from gentle slopes.



Watershed characteristics

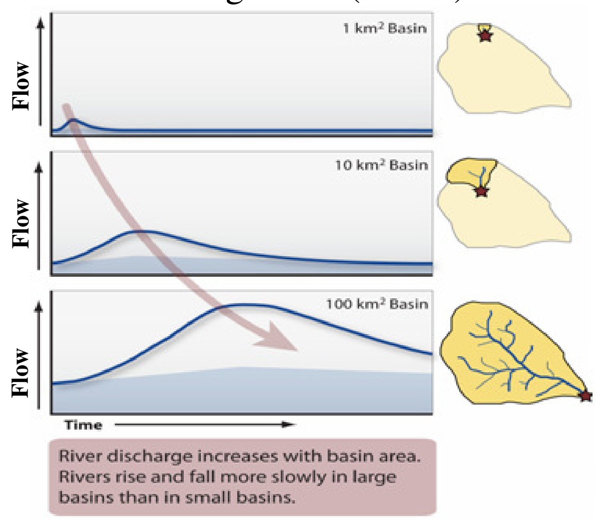
Example: watershed shape effect on the flow.



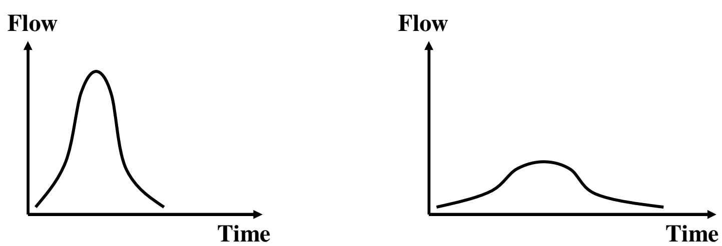
Watershed characteristics

Watershed contributing area:

Large areas contribute large flow (runoff).



Watershed characteristics



Case A

Case B

Steep watershed discharges flow like case …..

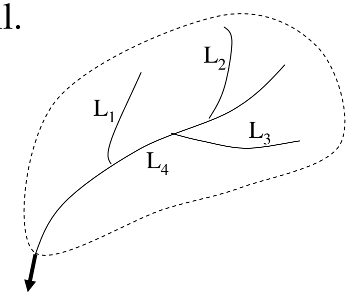
Watershed of rough surface discharges flow like case ….

Watershed characteristics

Drainage density:

The drainage density (D) is the ratio of the total length of all streams formed to the watershed area. The drainage density reflects the response of the watershed to the rainfall. It can be used to classify watersheds. Usually high D values means high and quick response (flow) of the watershed to rainfall.

$$D = \frac{\sum L}{A}$$



Watershed characteristics

Ex:

Watershed A of 4.1km^2 area has streams of 11.2km total length and watershed B of 0.58km^2 area has streams of 1.55km total length. If watershed A discharged peak flow of 1m^3/s from 30 minutes storm, estimate the peak flow resulted from watershed B when subjected to the same storm?

Soln:

$D_A = 11.2 / 4.10 = 2.73$

$D_B = 1.55 / 0.58 = 2.67$

Conclusion: $D_A \approx D_B$ (similar watersheds)

Watershed characteristics

Soln:

Since $D_A \approx D_B$, then the flow Q is proportion to area A, or the ratio $k = Q/A$ is constant.

$k_A \approx k_B$

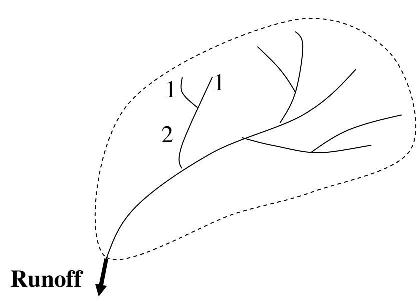
$$\frac{Q_A}{A_A} = \frac{Q_B}{A_B}$$

$Q_B = (0.58 \times 1)/4.1 = 0.141 m^3/s$.

Watershed Bifurcation

Stream order and Horton laws:

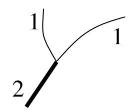
The stream order is used to classify watersheds. The order 1 is assigned to the smallest stream in the watershed, the order 2 is assigned to the next larger stream, and so on. The Horton laws can be used for computational purposes.



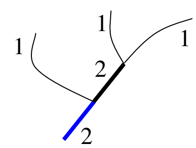
Watershed Bifurcation

Stream ordering rules:

When 2 streams of the same order (order i) are joined, the stream formed has the order of $i + 1$.



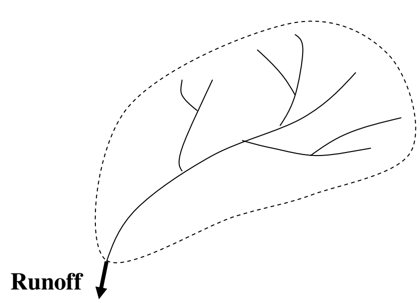
When a stream of order i meets a stream of order $i + 1$, then the stream formed has the order $i + 1$.



Watershed Bifurcation

Ex:

For the following watershed, order all streams and estimate the principal stream order.

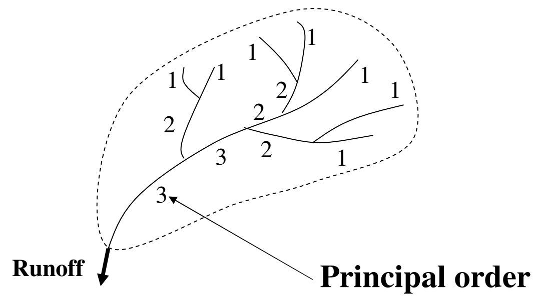


Watershed Bifurcation

Soln:

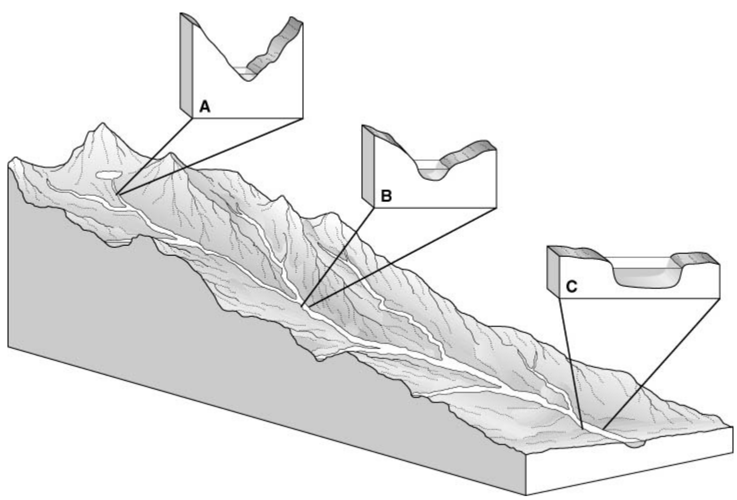
The first streams are labeled by the order 1, finish the solution using the rules mentioned previously. The principal order (k) = the largest order resulted.

$k = 3$



Watershed Bifurcation

Changes in stream properties in the watershed versus the order.



Watershed classification

Horton laws of streams:

Law of stream number (Bifurcation ratio):

$$\frac{N_i}{N_{i+1}} = R_n \longrightarrow N_i = R_n^{k-i}$$

where k is the principal stream order.

Law of stream length

$$\frac{L_{i+1}}{L_i} = R_L \longrightarrow L_i = L_1 R_L^{i-1}$$

Watershed characteristics

Exercise:

A watershed of 5.71km^2 area has principal stream order of 4. If streams of orders 3 and 4 have 1.23km and 0.45km total length respectively, compute the watershed drainage density?

What is the length of streams of order 6?

Statistical methods in hydrology

The design of surface water systems depends on natural hydrologic variable parameters like: precipitation, runoff, humidity, wind speed, etc. Such parameters are random variables.

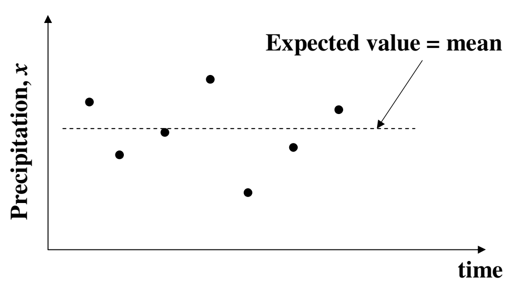
To deal with hydrologic random variables, statistical methods including the expectation, the variance, probability distribution functions, and frequency analysis are used. Such useful statistical methods will enable us to obtain the exceedance probabilities and return periods for design tasks, constructing IDF curves for computing peak flows for sewer sizing.

Statistical methods in hydrology

The expected value:

Given a historical record of hydrologic variable (X), for example the precipitation over n years, then the expected value (mean or average) of the variable is estimated as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

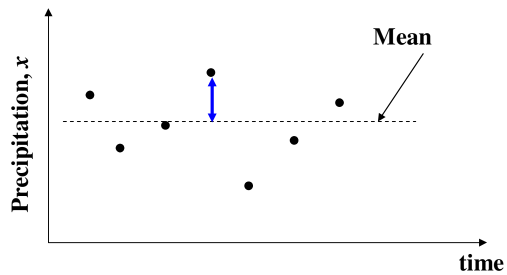


Statistical methods in hydrology

The variance and standard deviation:

Given a historical record of hydrologic variable (X), for example the precipitation over n years, then the variance is the squared deviation of the variable about its expected value (mean or average):

$$V = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2$$



The standard deviation $S = \sqrt{V}$

Statistical methods in hydrology

Example:

Given a historical record of rainfall depths (x) for years 1995 – 2010 at gauging station in Jordan. Estimate the mean and the standard deviation of the rainfall depth?

Year	Rainfall (mm)	Year	Rainfall (mm)
1995	212	2003	188
1996	123	2004	141
1997	156	2005	197
1998	225	2006	180
1999	134	2007	96
2000	175	2008	150
2001	237	2009	207
2002	249	2010	167

Statistical methods in hydrology

Soln: $n = 16$

Year	x_i	$(x_i - \bar{x})^2$	Year	x_i	$(x_i - \bar{x})^2$
1995	212	1203.2	2003	188	114.2
1996	123	2949.8	2004	141	1318.6
1997	156	454.2	2005	197	387.6
1998	225	2274.1	2006	180	7.2
1999	134	1876	2007	96	6611.7
2000	175	5.3	2008	150	746
2001	237	3562.6	2009	207	881.3
2002	249	5139.1	2010	167	106.3

Statistical methods in hydrology

The rainfall expected or mean value =

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{16} \times 2837 = 177.3 \text{ mm}$$

The standard deviation $S = \sqrt{V}$

$$S = \sqrt{V} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} = 42.9 \text{ mm}$$

Statistical methods in hydrology

Frequency analysis of hydrologic variables:

For design of water systems, given the exceedance probability of rainfall or flow as random variables, the design rainfall or flow amount can be obtained. The exceedance probability can be estimated by plotting the cumulative probability distribution.

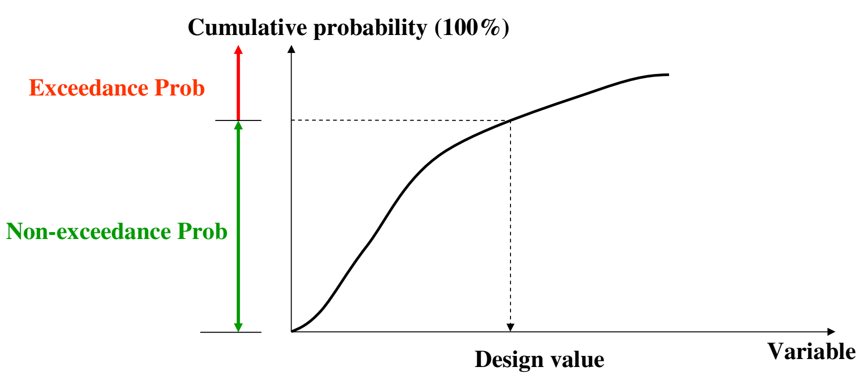
Examples from CE applications:

- Design flow for culverts,
- Design rain for collection systems (Sewers).

Statistical methods in hydrology

Obtaining the design value:

After drawing the cumulative probability and given the exceedance probability (failure occurrence 5% or 10% of time that is provided by the project owner), the design value can be obtained.



Statistical methods in hydrology

The computation of cumulative probability:

The exceedance probability can be estimated by plotting the cumulative probability distribution of the variable (rainfall or flow). Since the exact probability distribution function of the variable is hard to know, the plotting position equations can be used to plot the empirical cumulative distribution for the variable.

One of the most common equations to plot the empirical distribution is the **Weibull** plotting position equation.

Statistical methods in hydrology

The **Weibull** plotting position equation gives the non-exceedance probability $P(X \leq x)$ as:

$$P(X \leq x) = \frac{m}{n+1}$$

$P(X \leq x)$: probability of observing variable $\leq$ specified value x.
m: is data rank (lowest to highest).
n: record length.

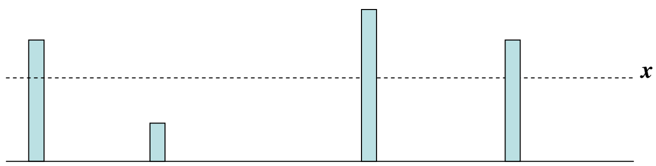
The probability $P(X > x) = 1 - P(X \leq x)$ is called the exceedance probability.

Statistical methods in hydrology

Given the exceedance probability $P(X > x)$, the return period T of the hydrologic variable that exceeds specified value (x) is:

$$T = \frac{1}{P(X > x)}$$

The return period defines on average how frequent or often the variable X will take time to exceed the value x.



Statistical methods in hydrology

Ex:

Annual rainfall at gauging station is recorded for years 1995 – 2010. Plot the distribution of the rainfall. Assuming that the design storm is 210mm, how frequent such rainfall storm will occur?

Year	Rainfall (mm)	Year	Rainfall (mm)
1995	212	2003	188
1996	123	2004	141
1997	156	2005	197
1998	225	2006	180
1999	134	2007	96
2000	175	2008	150
2001	237	2009	207
2002	249	2010	167

Statistical methods in hydrology

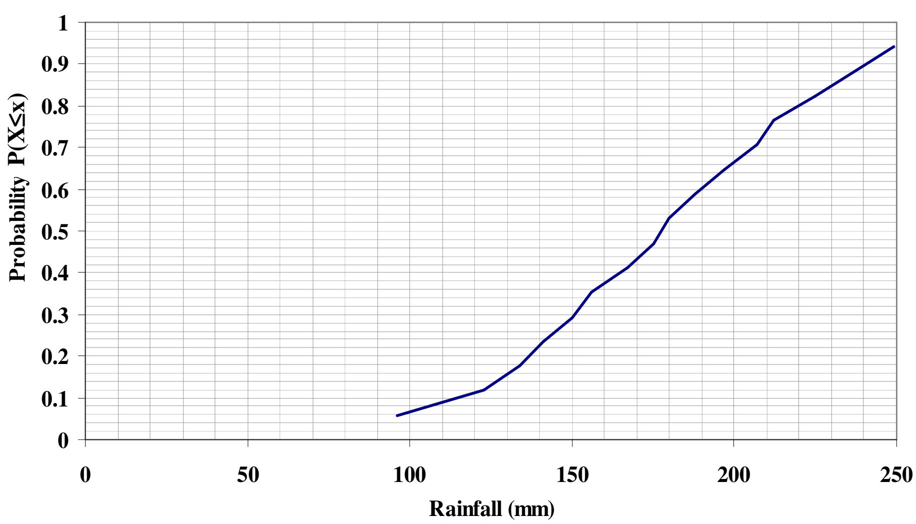
Soln: Arrange data from the lowest to highest. Rank the arranged data, and use the Weibull equation to calculate probability. $n = 16$.

Sample calculation: for $x = 96$, m = 1, then $P(X \leq x) = 1/(16+1) = 0.059$.

Rank (m)	Rainfall (x)	$P(X \leq x)$	Rank (m)	Rainfall (x)	$P(X \leq x)$
1	96	0.059	9	180	0.529
2	123	0.118	10	188	0.588
3	134	0.176	11	197	0.647
4	141	0.235	12	207	0.706
5	150	0.294	13	212	0.765
6	156	0.353	14	225	0.824
7	167	0.412	15	237	0.882
8	175	0.471	16	249	0.941

Statistical methods in hydrology

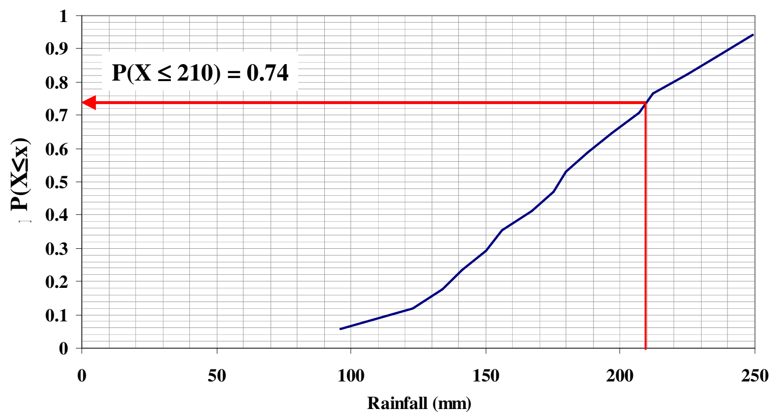
The probability distribution of the annual rainfall.



Statistical methods in hydrology

To find T for the design storm (210mm), then

P(X > x) = 1 – 0.74 = 0.26 and T = 1/0.26 = 3.86 ≈ 4years.



Question: estimate the design storm that being exceeded 40% of time?

Statistical methods in hydrology

Intensity Duration Frequency (IDF) curves:

Are set of curves that relate the maximum rainfall intensity (i) of a storm versus the duration (d) and the storm frequency (T years).

The rainfall intensity is defined as the ratio of the rainfall depth (mm) to the duration (hr),

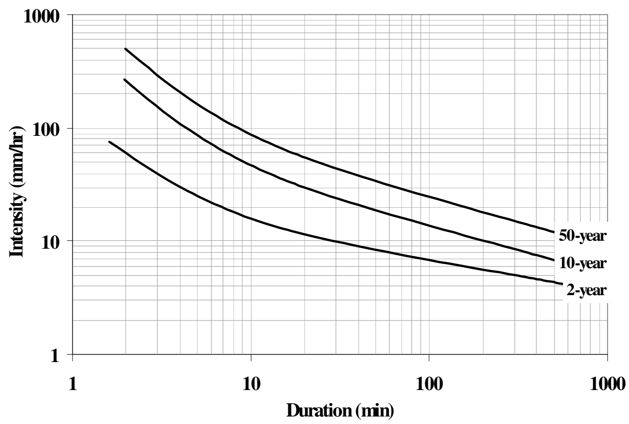
$$i(mm/hr) = \frac{x(mm)}{d(hr)}$$

Such curves are useful in computing the peak flow from small watersheds using the rational method.

Statistical methods in hydrology

IDF curves:

Are set of curves that relate the maximum rainfall intensity (i) of a storm versus the duration (d) and the storm frequency (T years).



Statistical methods in hydrology

To estimate the maximum storm intensity, we need at first to explore the maximum rainfall depth. The theoretical model that fits the distribution of the maximum rainfall depth of a given duration is the extreme value distribution type 1 (Gumbel distribution).

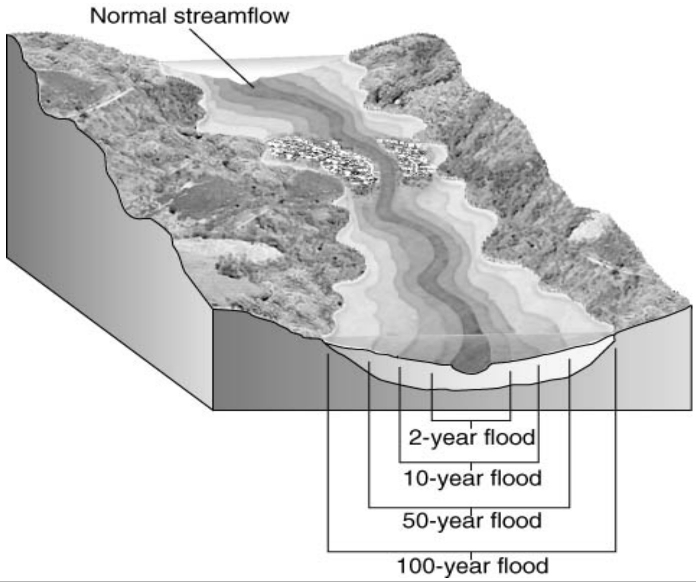
$$P(X \leq x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{x-u}{\alpha}\right]\right)\right]$$

α and u are the model parameters.

$$\alpha = \frac{\sqrt{6}\,S}{\pi} \qquad u = \bar{x} - 0.5772\,\alpha$$

Statistical methods in hydrology

Flow quantity in relation to frequency.



Statistical methods in hydrology

Ex:

Plot the theoretical distribution for the following 15-minute extreme rainfall depths.

Year	15-minute extreme rainfall depth (mm)
2000	12
2001	17
2002	7
2003	14
2004	27
2005	9
2006	13
2007	18
2008	8
2009	15
2010	11

Statistical methods in hydrology

Ex:

$\bar{x} = 13.72mm \qquad S = 5.64mm$

$$\alpha = \frac{\sqrt{6} \times 5.64}{\pi} = 4.4$$

$$u = 13.72 - 0.5772 \times 4.4 = 11.18$$

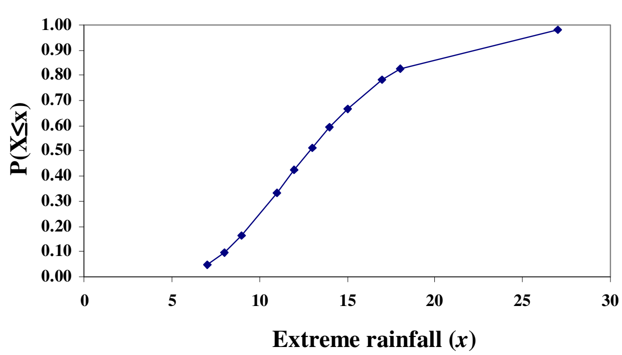
$$P(X \le x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{x-u}{\alpha}\right]\right)\right]$$

Statistical methods in hydrology

Ex:

$$P(X \le 7mm) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{7-11.18}{4.4}\right]\right)\right] = 0.08$$

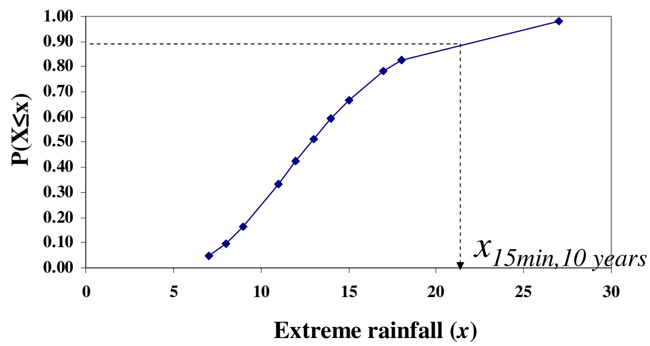
x	P(X ≤ x)
7	0.08
8	0.13
9	0.19
11	0.35
12	0.44
13	0.52
14	0.59
15	0.66
17	0.77
18	0.81
27	0.97



Statistical methods in hydrology

Question: what is the amount of the extreme rainfall depth that is associated to 15 mins duration and return period of 10 years, i.e. $x_{15min,10\ years}$

Answer: use the probability plot



Statistical methods in hydrology

The past question can be also answered using the frequency factor (K_T) of the Gumbel distribution as follows:

$$x_{d,T} = \bar{x}_d + K_T\, S_d$$

$x_{d,T}$: extreme rainfall depth for storm of duration d and frequency T years.

$\bar{x}_d$ and S_d: mean and standard deviation of extreme rainfall depths for storm of duration d (from records).

K_T: frequency factor of the Gumbel distribution.

$$K_T = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \mathbf{ln}\left(\mathbf{ln}\left[\frac{T}{T-1}\right]\right)\right]$$

Statistical methods in hydrology

Ex:

For the past 15-minute extreme rainfall depths, estimate the amount of the 15-minute rainfall depth associated to the 10-year return period

Year	15-minute extreme rainfall depth (mm)
2000	12
2001	17
2002	7
2003	14
2004	27
2005	9
2006	13
2007	18
2008	8
2009	15
2010	11

Statistical methods in hydrology

Ex:

$$K_T = K_{10} = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \mathbf{ln}\left(\mathbf{ln}\left[\frac{10}{10-1}\right]\right)\right] = 1.3$$

From the historical data

$$\bar{x}_d = \bar{x}_{15} = 13.72mm \qquad S_d = S_{15} = 5.64mm$$

then the amount of 15-min rainfall at T = 10 years is

$$x_{d,T} = \bar{x}_d + K_T\, S_d$$

$$x_{15\,\mathbf{min},10\,year} = \bar{x}_{15} + K_{10}\, S_{15} = 13.72 + 1.3 \times 5.64$$

$$x_{15\,\mathbf{min},10\,year} = 21mm$$

Statistical methods in hydrology

Steps to construct the IDF curves:

1. From precipitation records, for each year extract the max rainfall depths for durations: 5mins, 10, 15, 30mins, 1hr, 2, 6, and 24hrs.
2. Estimate the mean and standard deviation of max rainfall depths at the durations listed above.
3. Using the extreme value distribution estimate the frequency factor K_T and estimate the amount of rainfall depth ($x_{d,T}$) for durations listed at return periods of 2 years, 5, 10, 25, 50, and 100 years.
4. Correct the rainfall depths at the 2-year and 5-year return period by multiplying with 0.88 for the 2-year and 0.96 for the 5-year return period.

Statistical methods in hydrology

Steps to construct the IDF curves:

6. Calculate the rainfall intensity (i) in mm/hr units as:

$$i(mm/hr) = \frac{x_{d,T}}{d}$$

7. Plot the IDF curves. Place storm duration (d) at log scale on x-axis. Place the intensity (i) at log scale on the y-axis.

Statistical methods in hydrology

Ex:

Construct the 5-year IDF curve for the following max rainfall depths of 15-min and 60-min duration.

Year	15-min max rainfall	60-min max rainfall
2000	24	45
2001	30	75
2002	20	34

Soln:

for 15-min, $\bar{x}_{15} = 24.7mm \qquad S_{15} = 5mm$

for 60-min, $\bar{x}_{60} = 51.3mm \qquad S_{60} = 21.2mm$

$$K_5 = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left(\ln\left[\frac{5}{5-1}\right]\right)\right] = 0.72$$

Statistical methods in hydrology

Ex:

Soln: $x_{d,T} = \bar{x}_d + K_T\, S_d$

For 15-min, $x_{15,5}$ = 24.7 + 0.72×5 = 28.3mm

The corrected $x_{15,5}$ = 0.96×28.3 = 27.2mm,

$$i = \frac{27.2}{(15/60)} = 108.8 mm/hr$$

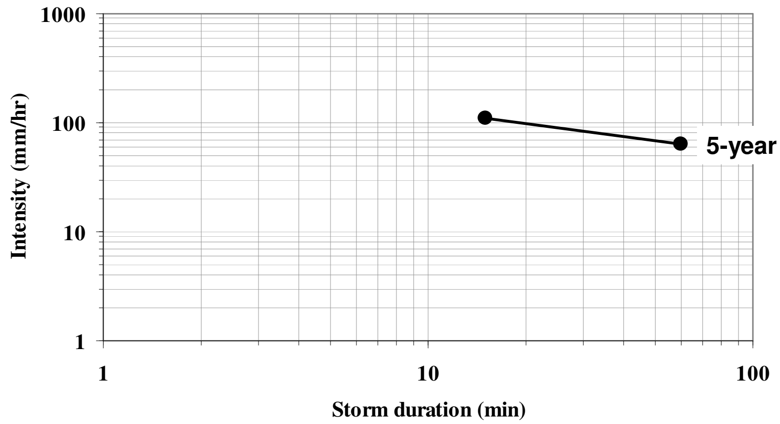
For 60-min, $x_{60,5}$ = 51.3 + 0.72×21.2 = 66.6mm

The corrected $x_{60,5}$ = 0.96×66.6 = 64mm,

$$i = \frac{64}{(60/60)} = 64 mm/hr$$

Statistical methods in hydrology

Ex: Result IDF for 5 years return period.



Micro-scale basin: measuring the runoff

The surface runoff (flow) from small watersheds can be estimated using the rational method benefiting of the IDF curves. In urban hydrology, the rational method is used to estimate the peak runoff for storm sewer design. The peak flow (m^3/s) is:

$$Q = 0.278\, C\, i\, A$$

C : runoff coefficient,

i : storm intensity (mm/h) obtained from IDF curves,

A : watershed contributing area (km^2).

Land Use or Type	C Value
Agriculture	
Bare Soil	0.20-0.60
Cultivated Fields (sandy soil)	0.20-0.40
Cultivated Fields (clay soil)	0.30-0.50
Grass	
Turf, Meadows	0.10-0.40
Steep Grassed Areas	0.50-0.70
Woodland	
Wooded Areas with Level Ground	0.05-0.25
Forested Areas with Steep Slopes	0.15-0.40
Bare Areas, Steep and Rocky	0.50-0.90
Roads	
Asphalt Pavement	0.80-0.90
Cobblestone or Concrete Pavement	0.60-0.85
Gravel Surface	0.40-0.80
Native Soil Surface	0.30-0.80
Urban Areas	
Residential, Flat	0.40-0.55
Residential, Moderately Steep	0.50-0.65
Commercial or Downtown	0.70-0.95

Micro-scale basin: measuring the runoff

The rational method is usually used conditioning to:

- the watershed area is small (< 3km^2).
- the watershed is nearly flat.
- the storm duration is ≥ the time of concentration.

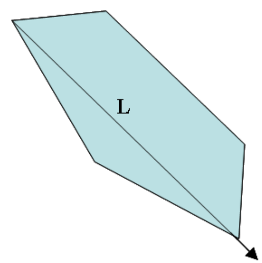
If the conditions mentioned above are not applicable, then the accuracy of the rational method is questionable. In that case the unit hydrograph, synthetic hydrographs and SCS method are used to estimate the peak runoff (will be discussed later).

Micro-scale basin: measuring the runoff

The time of concentration t_c:

For a given watershed, the time of concentration is defined as the time needed such that the whole watershed discharges flow. It is the longest time needed for a water drop to travel through the watershed to the final drainage point. Using the Kerby-Kirpich method, t_c in **minutes**:

$$t_c = \frac{0.828\left(L \times n\right)^{0.467}}{S^{0.235}}$$

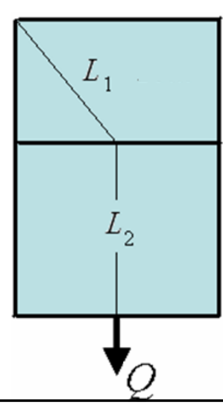


n: Roughness of surface
L: flow path distance (m)
S: surface slope

Micro-scale basin: measuring the runoff

Ex:

For the watershed shown below, estimate the peak flow from a storm of 2 years return period that lasts for 20mins (IDF curves given).

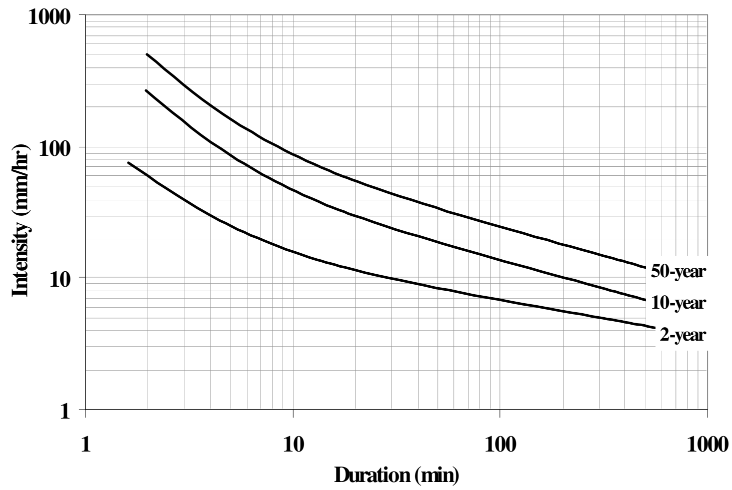


$C_1 = 0.8$, $A_1 = 40000$ m^2
$S_1 = 1\%$, $n_1 = 0.025$, L_1=220m

$C_2 = 0.9$, $A_2 = 50000$ m^2
$S_2 = 1.5\%$, $n_2 = 0.03$, L_2=250m

Micro-scale basin: measuring the runoff

IDF curves.



Micro-scale basin: measuring the runoff

Soln:

The time of concentration t_{c1} from sub-watershed 1=

$$= 0.828\times(220\times0.025)^{0.467}/0.01^{0.235} = 5.4 \text{ mins.}$$

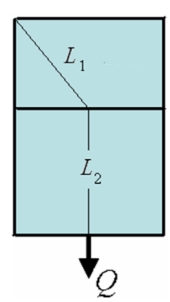
The time of concentration t_{c2} from sub-watershed 2=

$$= 0.828\times(250 \times0.03)^{0.467}/0.015^{0.235} = 5.7 \text{ mins.}$$

The time of concentration from the whole watershed =

$t_c = 5.4 + 5.7 = 11.1$ mins.

Why both times have been added?



Micro-scale basin: measuring the runoff

Soln:

The average watershed C =

$$C = \frac{(0.8 \times 40000) + (0.9 \times 50000)}{90000} = 0.86$$

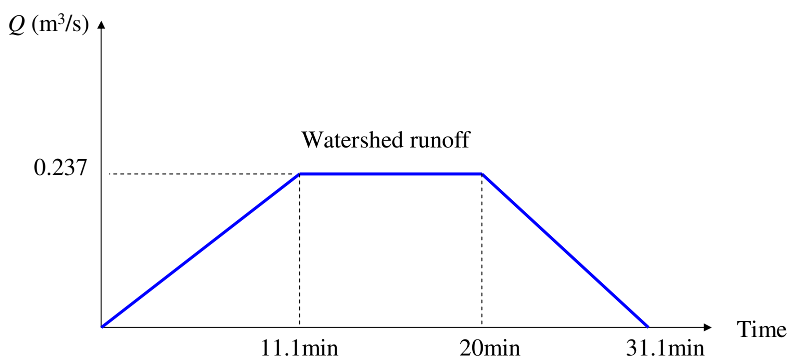
For t_c = 11.1mins < storm duration (20mins), and for T = 2 years then from the IDF-curves the storm intensity i = 11mm/h.

The peak flow $Q = 0.278 \times 0.86 \times 11 \times 0.09 = 0.237 \text{m}^3/\text{s}$

Micro-scale basin: measuring the runoff

Soln:

The resulted flow hydrograph (the hydrograph is defined as flow profile over the time).



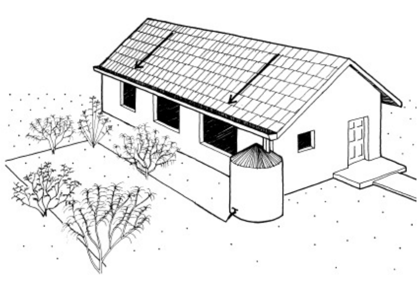
Micro-scale rainwater harvesting

Rainwater falls on small catchments (surfaces) will finally generate clean water runoff (flow) that can be collected as potential water source. Such small catchments can be: house rooftop, paved street or parking lot. The quality of such collected water is considered acceptable for drinking (give an example from the Jordanian heritage), gardening and cleaning purposes.

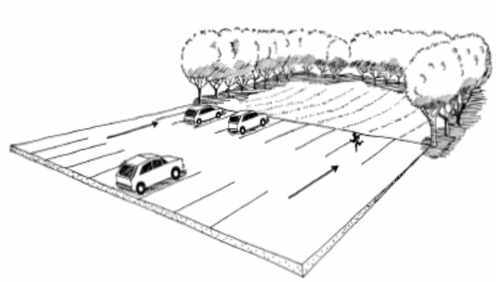
At an average rainy season, each single house rooftop in Jordan is able to collect about $10m^3$ of clean water. Just imagine that: if 50% of Jordanian house conduct such technique, what would be the amount of water collected? Do the simple math?

Micro-scale rainwater harvesting

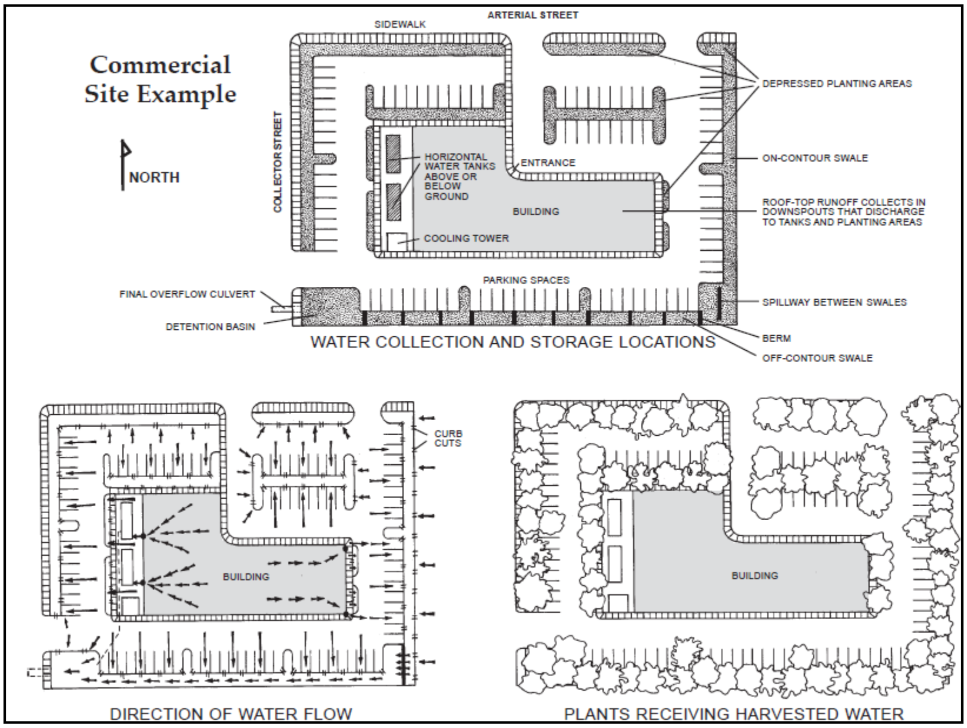
Example: micro-scale rainwater harvesting projects.



House rooftop

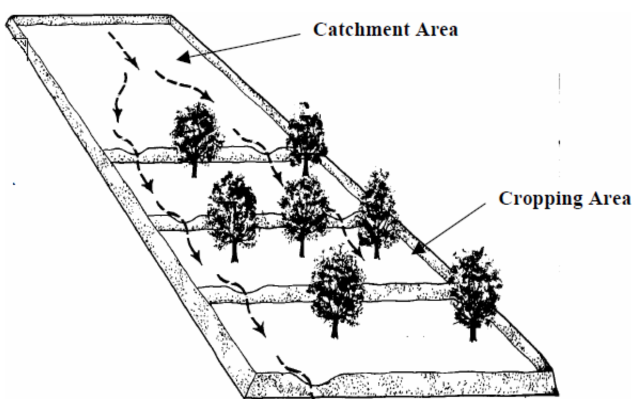


Parking lot



Micro-scale rainwater harvesting

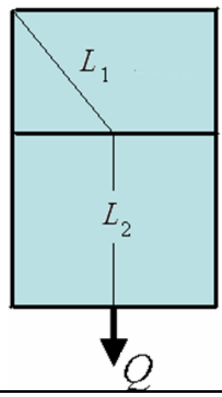
Example: micro-scale rainwater harvesting project (Cascade cropping area).



Micro-scale rainwater harvesting

Ex:

For the watershed shown in the previous example, estimate the maximum potential water volume that can be harvested from the storm given.



$C_1 = 0.8$, $A_1 = 40000$ m^2

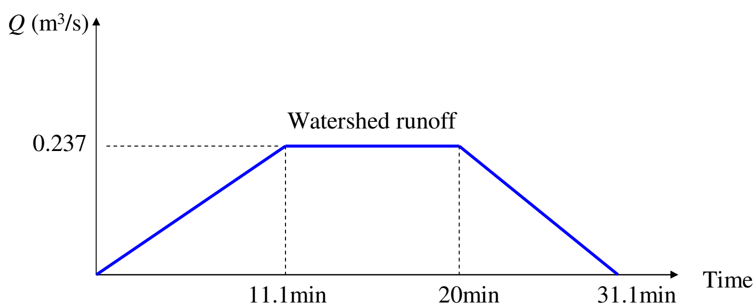
$S_1 = 1\%$, $n_1 = 0.025$, L_1=220m

$C_2 = 0.9$, $A_2 = 50000$ m^2

$S_2 = 1.5\%$, $n_2 = 0.03$, L_2=250m

Micro-scale rainwater harvesting

Soln: given the hydrograph below.



The water volume possibly harvested from such watershed is the area under the runoff curve:

$V = Q \times$ time

$= 2\times(0.5\times11.1\times60\times0.237) + (20 - 11.1)\times60 \times0.237$

$= 284$m^3

Engineering Hydrology

110401454

Hydrologic parameters

Instructor: Dr. Zeyad Tarawneh

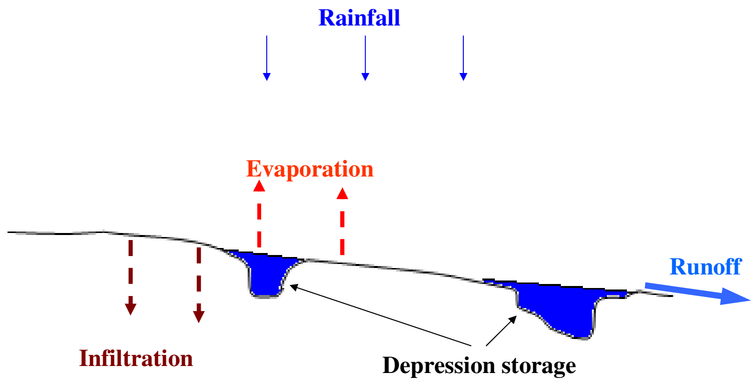
Macro-scale basin: measuring the runoff

The estimation of the surface runoff generated from large basins (Macro-scale) depends on estimating the losses from the total precipitation. Such losses are: evaporation, soil infiltration, surface storage and surface interception (depends on surface roughness and vegetation cover).

After abstracting (deducting) losses from the total precipitation, the net rain (**excess rain**) will run on the land surface forming the surface runoff.

The task is to compute the excess (net) rainfall after deducting the losses from the total precipitation.

Hydrologic parameters



Hydrologic parameters: precipitation

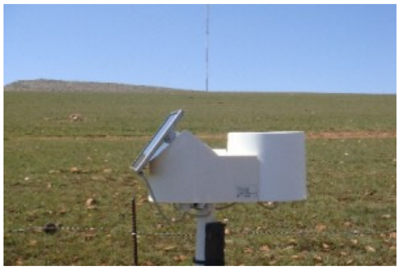
The first hydrologic parameter to be considered for the analysis is the precipitation. It is considered as the primary input variable in the hydrologic cycle and has the following forms: rain, snow or hail.

Precipitation is derived mainly from the atmospheric water, therefore its form (rain, snow,..) and quantity are being influenced by climatic variables like wind, temperature and atmospheric pressure.

Precipitation is a random variable having spatial and temporal (time) variability.

Measuring the precipitation

Precipitation is measured in gauging stations. The unit to measure precipitation is mm depth.



Automated rainfall gauge

Traditional rainfall gauge

Estimating the precipitation

For some applications in hydrology, it is necessary to estimate the precipitation at un-gauged site (location without gauging station). Precipitation can be estimated based on point or areal methodology.

The point estimation of precipitation can be made using the weighted average distance method developed by the National Weather Service. Given precipitation at gauged sites and the distances between the gauged sites and un-gauged site, the precipitation at the un-gauged site can be obtained.

Estimating the precipitation

The point estimation of the un-gauged site precipitation is:

$$P_{un-gauged} = \frac{\sum P \times W}{\sum W}$$

Where

P: the gauged site precipitation

W: the gauged site weighted distance, $W = 1/D^2$,

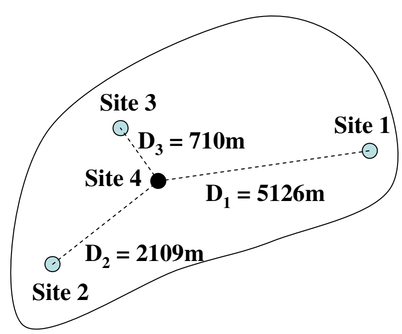
D: distance between the gauged and un-gauged site

Estimating the precipitation

Ex:

Estimate the rainfall at the un-gauged site # 4 based on the rainfall at the following gauged sites.

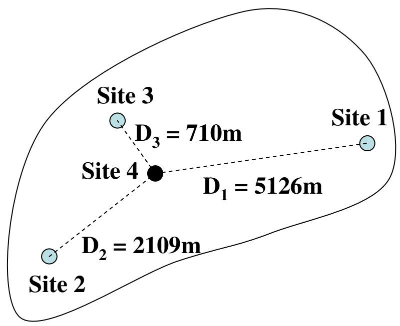
Site	rainfall (mm)
1	14
2	21
3	11



Estimating the precipitation

Soln:

Site	rainfall (mm)	*D* (km)	*W*	*P*×*W*
1	14	5.126	0.038	0.533
2	21	2.109	0.225	4.721
3	11	0.710	1.984	21.821
		$\sum W =$	2.247	$\sum W \times P =$ 27.075



$$P_{site4} = \frac{\sum P \times W}{\sum W}$$

$$P_{site4} = \frac{27.075}{2.247} = 12.05mm$$

Estimating the precipitation

The average precipitation over the watershed is an important hydrologic parameter. The areal (average) precipitation can be found using the Thiessen polygon method:

$$\overline{P} = \frac{\sum P \times A}{\sum A}$$

Where

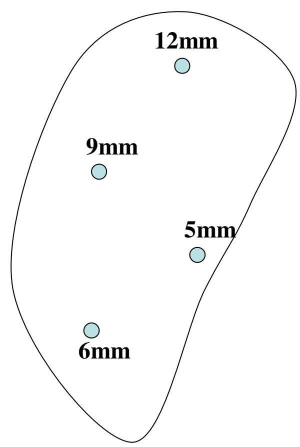
P: the precipitation in the thiessen polygon

A: area formed by thiessen polygons.

Estimating the precipitation

Ex:

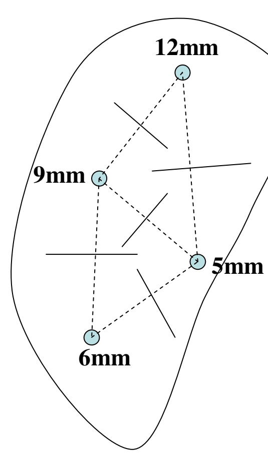
Estimate the areal rainfall for the following watershed.



Estimating the precipitation

Soln:

Connect the sites and bisect the distance between sites.



Estimating the precipitation

Soln:

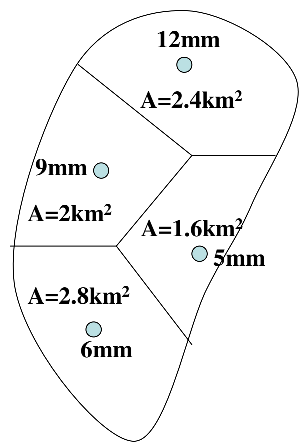
Calculate the area entrapped by each polygon.

Assume area are calculated as shown below.

A	$P \times A$
2.4	28.8
2.0	18.0
1.6	8.0
2.8	16.8

$\sum A = 8.8 \qquad \sum P \times A = 71.6$

$$\overline{P} = \frac{\sum P \times A}{\sum A} = 8.14mm$$



Hydrologic parameters: evaporation

The net rain (excess) that generates surface runoff is that part of the total precipitation after deducting the evaporated, the intercepted, the infiltrated and the precipitation that is stored in depressions (small holes in the surface).

The evaporated precipitation depends on the temperature, wind speed, relative humidity, soil condition, and type of vegetation cover. High evaporation rates reduces the potential runoff. The evaporation is usually measured experimentally using evaporation pans. The units of the evaporation is (mm/hr).

Estimating the evaporation

Theoretically, the evaporated precipitation can be estimated using the energy balance method adjusted for the soil and the vegetation cover:

$$E_r(m/s) = \frac{R_n}{l_v \rho} \times k_s \times k_c$$

Where
R_n: net solar radiation (W/m^2),
ρ: water density ($1000 kg/m^3$),
l_v: latent heat of vaporization (J/kg),
k_s: soil coefficient, usually $k_s = 1$ for complete wet soil,
k_c: vegetation cover coefficient, usually $k_c = 1$ in arid regions.
In units (KJ/kg), the latent heat is $l_v = 2500 - 2.36\,T$
T: temperature (°C)

Estimating the evaporation

Ex:

Calculate the evaporation rate under net solar radiation of 200 W/m^2 and air temperature of 25 °C. Assume completely wet soil ($k_s = 1$) in arid region ($k_c = 1$).

Soln:

$l_v = 2500 - 2.36\,T = 2500 - 2.36\,(25) = 2441$ KJ/kg

$$E_r = \frac{R_n}{l_v \rho} \times k_s \times k_c = \frac{200}{2441000 \times 1000} \times 1 \times 1 =$$

$= 8.22 \times 10^{-8}$ m/s
$= 7.1$ mm/day

Hydrologic parameters: interception

The intercepted water is the part of precipitation that is intercepted by plant leaves. Therefore the leave size and the intensity of leaves highly affect the amount of water intercepted that will evaporate eventually and hence reducing the runoff.

The interception can be measured experimentally in the lab. In arid regions like Jordan, the plant cover is small while the evaporation rate is high, therefore the intercepted water can be neglected compared to the evaporated.

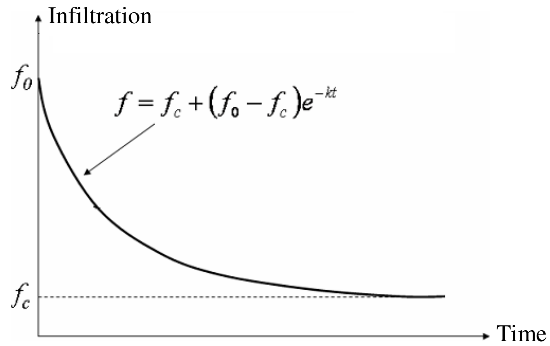
Hydrologic parameters: infiltration

The infiltrated precipitation depends on the soil type, rainfall intensity, surface conditions, and the vegetation cover. Horton suggested the following model to estimate the infiltrated water:

$$f = f_c + \left(f_0 - f_c\right)e^{-kt}$$

f : infiltration amount (mm/hr)
f_c : equilibrium infiltration capacity (mm/hr)
f_0 : initial infiltration capacity (mm/hr)
k : infiltration constant (1/hr)
t : time (hrs)

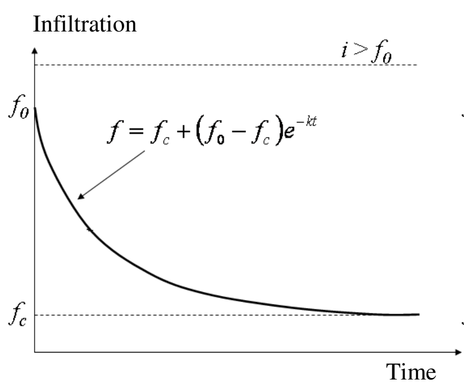
Hydrologic parameters



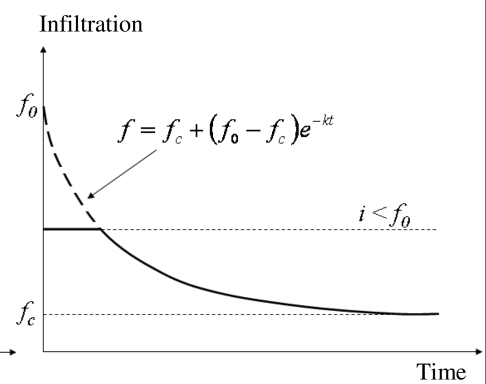
At time $t = 0$, the infiltration begins with its the initial infiltration rate f_0, however as time proceeds the infiltration rate decreases to reach its equilibrium infiltration f_c.

Hydrologic parameters

Consider the following cases.



Case1:
Precipitation > initial infiltration



Case2:
Precipitation < initial infiltration

Hydrologic parameters: depression storage

The precipitation stored in depressions is that part stored in small holes in land surface. It will eventually evaporate. Depression storage highly affects the runoff from storms of short duration with low precipitation intensity. The depression storage is:

$$D_S = S_c\left(1 - e^{-P_n / S_c}\right)$$

D_S: water stored (mm/hr)
S_c: total storage capacity (mm/hr)
P_n: net rainfall for storage (mm/hr)
P_n = total rainfall – evaporation – interception – infiltration

Hydrologic parameters

Ex:

A 2hrs rainfall storm with pattern as shown below. Given the soil equilibrium infiltration capacity of 0.75mm/hr, an initial infiltration of 5mm/hr, and the infiltration constant is 0.29, what is the net rain available for runoff assuming that depression storage is for the first hour with total storage capacity of 2mm/hr. Assume completely wet soil in arid region under air temperature of 10°C and solar radiation of 150W/m^2. Neglect interception losses.

Hour	Total rainfall intensity (mm/hr)
1	10.3
2	12.5

Hydrologic parameters

Soln: $l_v = 2500 - 2.36\,T = 2500 - 2.36\,(10) = 2476.4$ KJ/kg
$E_r = 150/(2476400\times1000) = 0.22$mm/hr

For the first hour, the infiltrated water is:

$$f = 0.75 + [5 - 0.75]e^{-0.29\times1} = 3.93\text{mm/hr}$$

The net rain for storage P_n =
= precipitation – evaporation – interception – infiltration
= 10.3 – 0.22 – 0 – 3.93 = 6.15mm/hr

The depression storage:

$$D_S = 2\,[1 - e^{(-\,6.15/2)}] = 1.9\text{mm/hr}$$

The net rain available for runoff = 10.3 – 0.22 – 3.93 – 1.9
= 4.25mm/hr

Hydrologic parameters

The following table shows the results over the 2 hours storm.

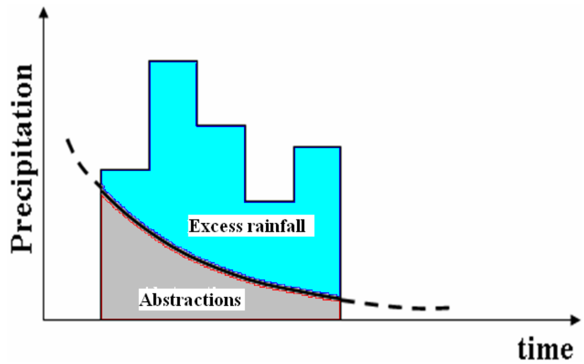
Hour	Gross rainfall intensity (mm/hr)	E_r (mm/hr)	f (mm/hr)	P_n (mm/hr)	D_S (mm/hr)	Net rain (mm/hr)
1	10.3	0.22	3.93	6.15	1.92	4.25
2	12.5	0.22	3.13	9.15	0	9.15

Note that storage = 0 for the 2nd hour

Hydrologic parameters

SCS method for deducting abstractions:

The Soil Conservation Services (SCS) developed a method to calculate the excess rain available for runoff. Excess rain is the total rain after deducting all abstractions.



Hydrologic parameters

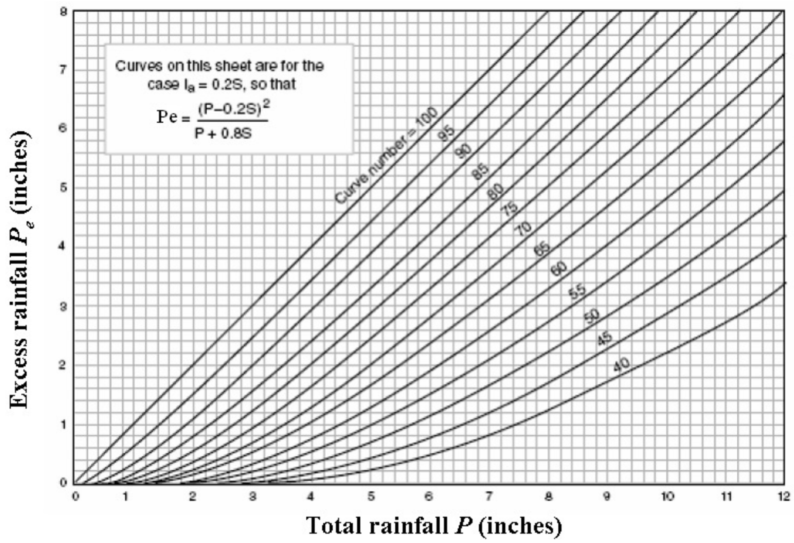
The SCS developed the method to calculate the excess rain for nearly flat watersheds (slope ≤ 5%). What will be the case for watersheds of slope > 5%? Think about it?.

The method considers the watershed soil type, land cover, and the antecedent moisture condition (AMC) based on the 5-day antecedent rainfall.

Based on huge number of observations, the SCS method resulted in many curves that relate the excess rain available for the direct runoff versus the total rainfall when the antecedent moisture condition is average (AMC II). For moisture conditions rather than the average a slight modification is needed.

Hydrologic parameters

SCS curve number for soils (AMC II).



Hydrologic parameters

The SCS classified the antecedent moisture condition (AMC) as follows: AMC I for dry soil, AMC II for soil with average moisture, and AMC III for wet soil.

The SCS classified the soil as follows:

Group A: Deep sands, silts

Group B: Sandy loam

Group C: Clay loam, shallow sandy loam

Group D: Soils that swell significantly, plastic clays.

Hydrologic parameters

The SCS method supplies a Curve Number (CN) according to the land cover and soil group based on AMC II condition. For example refer to the table below.

Land use	Hydrologic soil group			
	A	B	C	D
Cultivated lands	72	81	88	91
Range lands	39	61	74	80
Forest land	45	66	77	83
Desert land	63	77	85	88

Hydrologic parameters

Having the CN determined for the watershed, then the maximum retention storage *S* (max rain can be stored) in inches is:

$$S = \frac{1000}{CN} - 10$$

The excess rain (**in inches**) for the direct runoff is:

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

Hydrologic parameters

SCS method for abstractions:

Given the CN at AMC II, the equivalent CN at AMC I and at AMC III is found as:

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

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

Hydrologic parameters

Ex:

Determine the excess rain of the 3 inches total rain on nearly flat clay loam watershed of $18km^2$ under dry soil condition. Among the $18km^2$, $7km^2$ is range land, while the rest is cultivated land.

Soln:

AMC for the whole watershed is AMC I,

Hydrologic soil group is C,

The CN of the $7km^2$ part = 74,

The CN of the $11km^2$ part = 88,

The weighted average CN = (7×74 + 11×88)/18 = 82.5

Hydrologic parameters

Soln:

The average CN = 82.5 is based on moisture condition of the AMC II type. The CN(I) for the AMC I is:

$$CN(I)=\frac{4.2CN(II)}{10-0.058CN(II)}=\frac{4.2\times 82.5}{10-0.058\times 82.5}=66.5$$

The max potential retention *S* is:

$$S=\frac{1000}{CN}-10=\frac{1000}{66.5}-10=5.03\,inches$$

The excess rainfall for the direct runoff is:

$$P_e=\frac{(P-0.2S)^2}{(P+0.8S)}=\frac{(3-0.2\times 5.03)^2}{(3+0.8\times 5.03)}=0.56\,inches$$

Engineering Hydrology

110401454

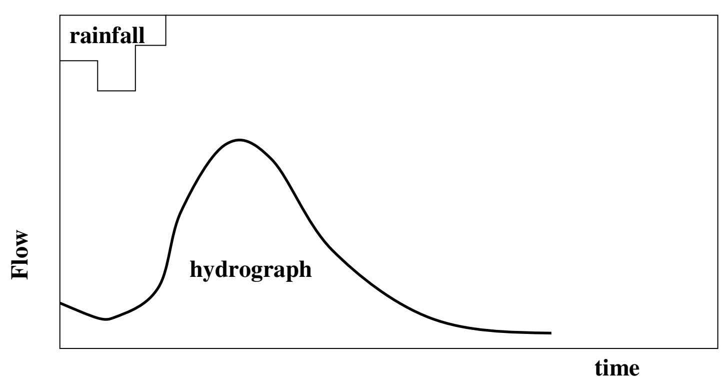
Macro-scale basin: measuring the runoff

Instructor: Dr. Zeyad Tarawneh

Hydrograph

The hydrograph is a graphical presentation that describes how the surface runoff develops over the time from the beginning of the rainfall and thereafter.

The following plot shows a typical hydrograph versus the cause: rainfall.



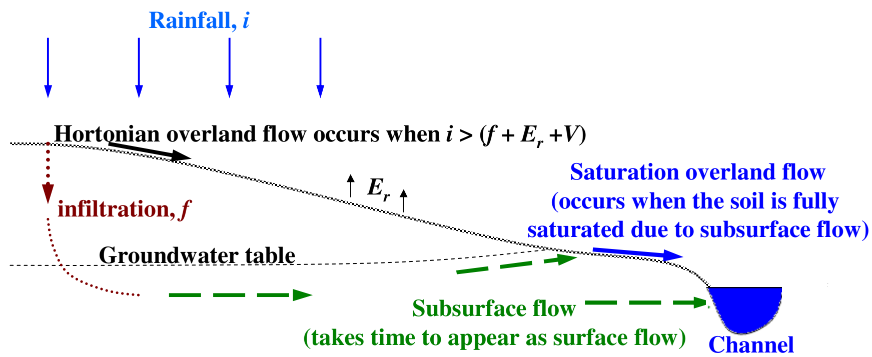
Hydrograph

The surface runoff (Hortonian overland flow) depends on many factors like: the rainfall duration and intensity (i and d), the evaporation (E_r), the infiltration (f), depression storage (D_s).

The saturated surface (overland) flow occurs when the soil top layer is fully saturated due to subsurface flow (groundwater flow). Based on that, the total surface runoff consists of the saturated overland flow and the base flow from under-surface.

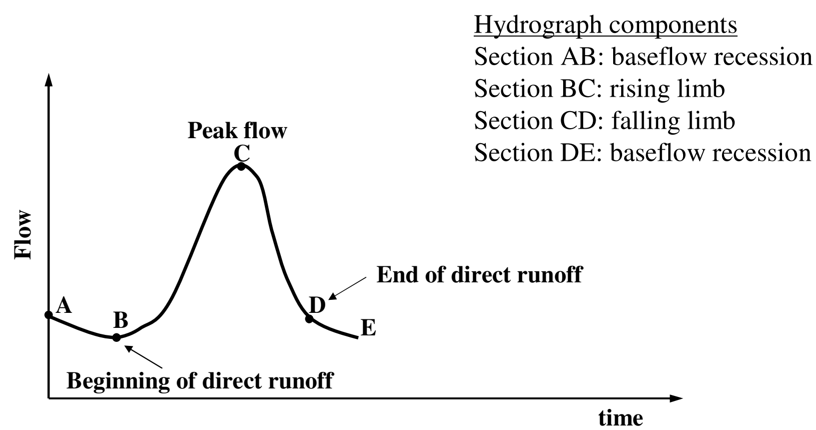
Hydrograph

The following schematic plot defines the Hortonian overland flow, the subsurface flow, and the saturation overland flow.



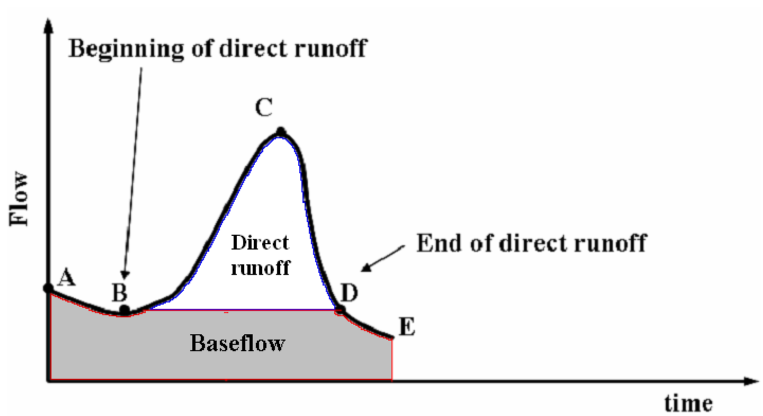
Hydrograph

The following schematic plot defines a typical surface flow hydrograph from a watershed.



Hydrograph

From the total runoff hydrograph, it can be seen that the runoff consists of two portions. The first portion is the baseflow (groundwater flow), and the second portion is the direct runoff (surface runoff = overland flow).



Hydrograph

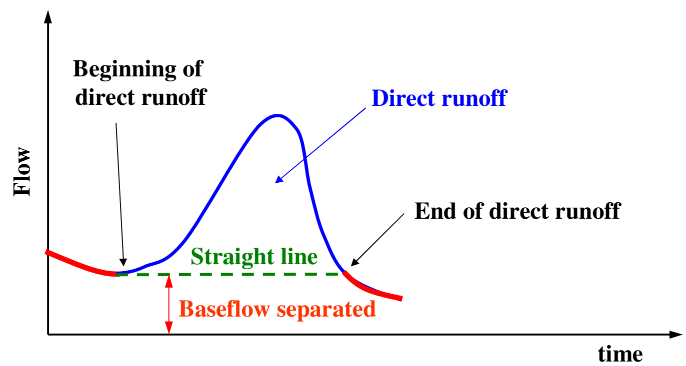
To study the watershed response (the direct runoff = surface runoff = overland flow) due to the cause (rainfall), then given the total runoff from the watershed, the base flow must be separated (extracted).

In literature, there are several methods to separate the baseflow (to estimate its quantity) among these are: the straight line method, the fixed base method, and the variable slope method.

In this course, the straight line method will be adopted to separate the base flow from the total runoff.

Hydrograph

The straight line method: to separate the baseflow, construct a straight horizontal line at the beginning of the rising limb of the hydrograph.



Hydrograph

Ex:

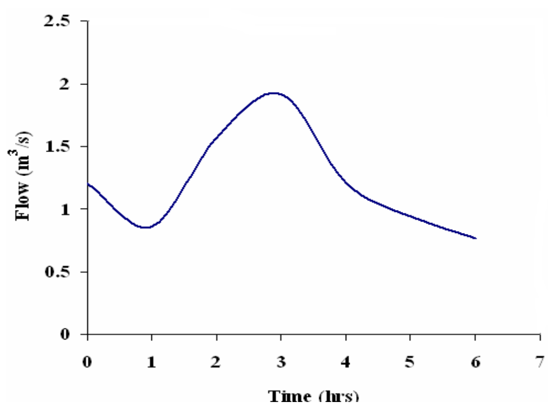
A large watershed discharges runoff to its outlet. The measured total runoff is shown in the table below. Estimate the direct runoff (surface runoff)?

Time (hr)	Total Runoff (m^3/s)
0	1.2
1	0.86
2	1.57
3	1.92
4	1.21
5	0.94
6	0.77

Hydrograph

Soln:

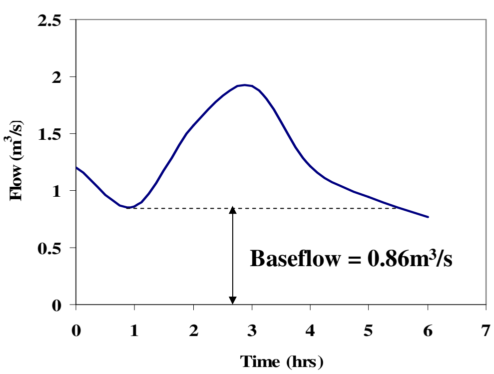
The following plot shows the hydrograph of the watershed total runoff. Observe the base flow recession portion and the rising limb. The baseflow will be at first separated using the straight line method.



Hydrograph

Soln:

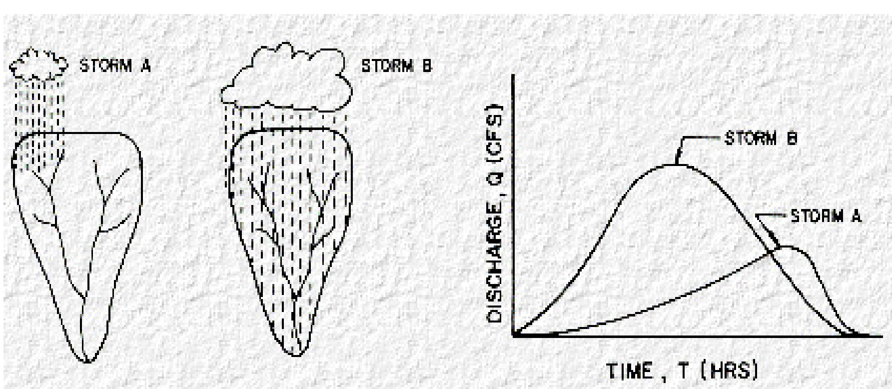
The direct runoff can be obtained after separating (subtracting) the baseflow from the total runoff. The direct runoff is the watershed response that will be used to derive the Unit Hydrograph.



Time	Total runoff	Baseflow	Direct runoff
0	1.2	1.2	0
1	0.86	0.86	0
2	1.57	0.86	0.71
3	1.92	0.86	1.06
4	1.21	0.86	0.35
5	0.94	0.86	0.08
6	0.77	0.77	0

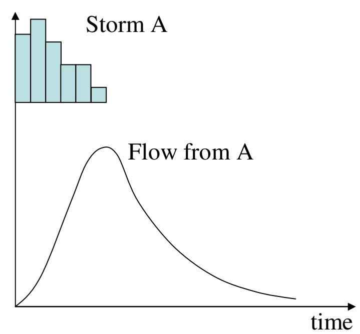
Hydrograph

Explain the following hydrographs resulted from storms A and B, i.e. observe the effect of storm size.



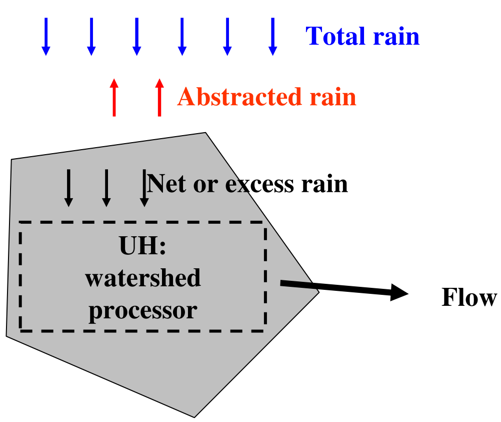
Hydrograph

Explain the following hydrographs resulted from storms A and B, i.e. observe the effect of storm shape.



Unit Hydrograph (UH)

The peak flow from small watersheds (< 3km^2) can be estimated using the rational method. For large watersheds, the resulted flow and peak flow can be computed using the Unit Hydrograph (UH).



Unit Hydrograph (UH)

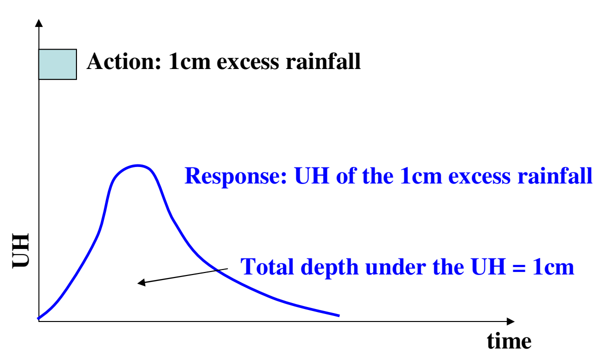
Therefore, the UH is defined as the watershed response through its direct runoff to an excess (net) rainfall of 1cm depth (unit depth). If the duration of the 1cm excess rainfall is X hrs, then the produced UH is called the X-hr UH. For example: 1-hr UH, 2-hr UH, and so on.

Assumptions:

- The excess rainfall has constant intensity,
- The excess rainfall is distributed uniformly over the entire catchment.

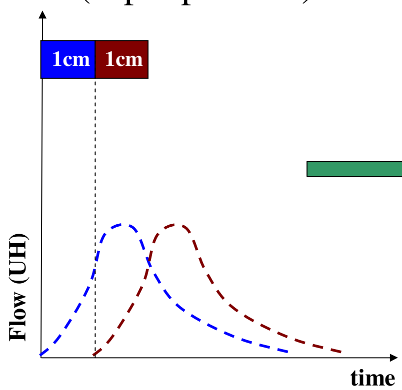
Unit Hydrograph

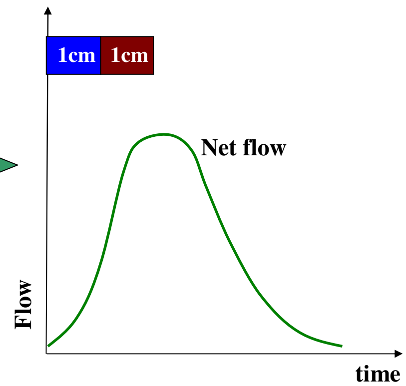
The plot below presents the idea of the UH. The action (pulse) is the 1cm excess rainfall. The response is the direct runoff that has total depth of 1cm, distributed over the time according to the water travel time to the watershed outlet.



Unit Hydrograph

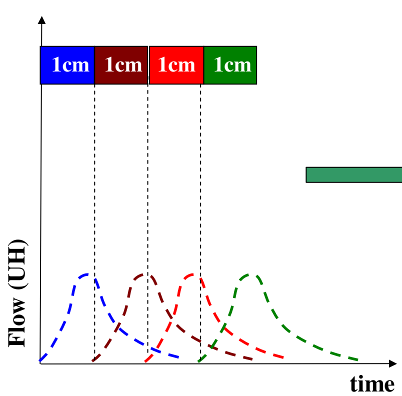
Assume a watershed of X-hr UH is subjected to a 1 cm net rain storm of 2X duration, then the storm has 2 pulses each of X duration and 1cm excess rain. Each will produce its own flow and the net flow will be the sum (super position) of the two flows.

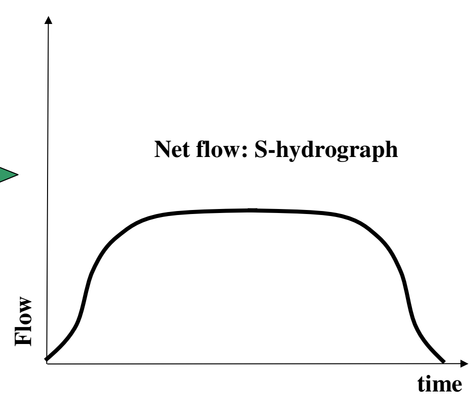




Unit Hydrograph

Assume many pulses each of X duration and has 1cm excess rain. The net flow is called the S-hydrograph.





Usefulness of Unit Hydrograph

If the watershed UH is known and given the net rainfall (P), then the runoff Q (flow) resulted from the watershed can be computed using the general equation:

$$Q = P \times UH$$

However, if the watershed UH is unknown, then it can be derived given P and Q from gauging stations, or

$$UH = Q / P$$

Measuring the runoff given UH

Given the UH and the excess rainfall (P_m), the resulted direct runoff (Q_n) from the watershed is computed as follows:

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1}$$

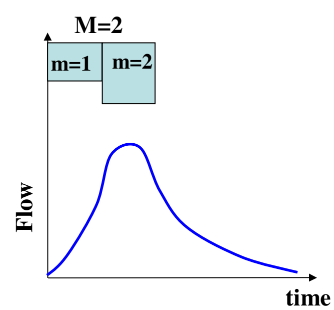
where

n: runoff time step (usually hr)

M: total # of rainfall pulses

m: rainfall pulse #

U_{n-m+1}: is the unit hydrograph value at time $n - m + 1$.



Measuring the runoff given UH

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1}$$

The runoff equation above can be re-written as follows:

$$Q_n = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + \ldots + P_n U_1$$

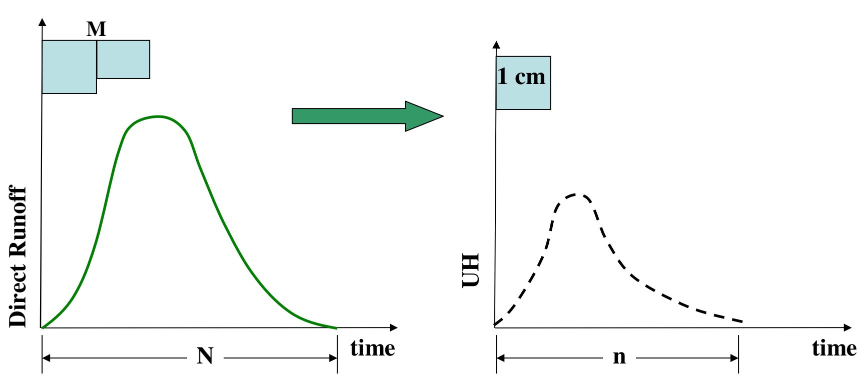
Question:

Assume storm of 2 pulses (P_1 and P_2), write the equation above?

Deriving the UH

Given the direct runoff (flow) Q over N time steps and the excess rainfall P over M time steps, then the UH as watershed response extends over n time steps.

$n = N - M + 1$.



Deriving the UH

$$Q_n = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + ... + P_n U_1$$

From the equation above it can be seen that:

at n = 1, $Q_1 = P_1 U_1 \Longrightarrow U_1 = \dfrac{Q_1}{P_1}$

at n = 2, $Q_2 = P_1 U_2 + P_2 U_1 \Longrightarrow U_2 = \dfrac{Q_2 - P_2 U_1}{P_1}$

and so on……

Deriving the UH

Ex:

Watershed of 6.23 km^2 area discharges flow from 2-hr storm with excess rainfall as shown in the table. Derive the 1-hr UH.

Time (hr)	Excess rainfall (mm)	Direct runoff (m^3/s)
1	20	2.3
2	15	12.1
3		26.7
4		17.2
5		2.3

Deriving the UH

Soln:

From the table, $N = 5$, $M = 2$, then $n = N - M + 1$, so $n = 4$.

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1} \;=\; P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + \ldots + P_n U_1$$

for $n = 1$, $\quad Q_1 = \sum_{m=1}^{1} P_m U_{1-m+1} = P_1 U_1$

for $n = 2$, $\quad Q_2 = \sum_{m=1}^{2} P_m U_{2-m+1} = P_1 U_2 + P_2 U_1$

for n = 3, $\quad Q_3 = \sum_{m=1}^{2} P_m U_{3-m+1} = P_1 U_3 + P_2 U_2 \quad$ and so on ….

Deriving the UH

Soln:

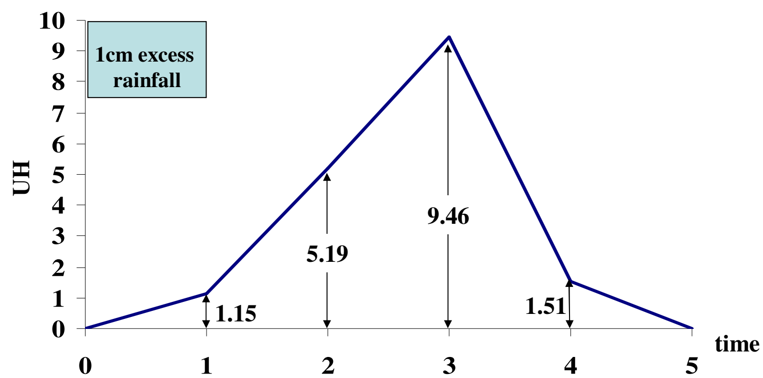
Results are shown below.

Time (hr)	Excess rainfall (cm)	Direct runoff (m^3/s)	Equation	UH ($m^3/s/cm$)
1	$P_1 = 2.0$	$Q_1 = 2.3$	$Q_1 = P_1 U_1$	$U_1 = 1.15$
2	$P_2 = 1.5$	$Q_2 = 12.1$	$Q_2 = P_1 U_2 + P_2 U_1$	$U_2 = 5.19$
3		$Q_3 = 26.7$	$Q_3 = P_1 U_3 + P_2 U_2$	$U_3 = 9.46$
4		$Q_4 = 17.2$	$Q_4 = P_1 U_4 + P_2 U_3$	$U_4 = 1.51$
5		$Q_5 = 2.3$		

Cause **Response** **Response to 1cm**

Deriving the UH

Each 1-hr storm of 1cm excess rainfall will have the following UH.



Application on the UH

Ex:

For the watershed of 6.23 km^2 area and given the UH from the previous example, draw the direct runoff hydrograph and find the peak runoff from 3-hrs storm of excess rainfall as shown below.

Time (hr)	Excess rainfall (mm)
1	8
2	10
3	5

Measuring the surface runoff

Soln:

Given the UH derived in the previous example, the runoff amount of the 3-hr storm can be obtained as follows:

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1} = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + \ldots + P_n U_1$$

at $n = 1$, $Q_1 = \sum_{m=1}^{1} P_m U_{1-m+1} = P_1 U_1 = 0.8 \times 1.15 = 0.92 \text{m}^3/\text{s}$

at $n = 2$, $Q_2 = \sum_{m=1}^{2} P_m U_{2-m+1} = P_1 U_2 + P_2 U_1$

$= 0.8 \times 5.19 + 1 \times 1.15 = 5.3 \text{m}^3/\text{s}$.

Measuring the surface runoff

at $n = 3$, $Q_3 = \sum_{m=1}^{3} P_m U_{3-m+1} = P_1 U_3 + P_2 U_2 + P_3 U_1$

$= 0.8 \times 9.46 + 1 \times 5.19 + 0.5 \times 1.15 = 13.33 \text{m}^3/\text{s}$

Why 3 ??

at $n = 4$, $Q_4 = \sum_{m=1}^{3} P_m U_{4-m+1} = P_1 U_4 + P_2 U_3 + P_3 U_2$

$= 0.8 \times 1.51 + 1 \times 9.46 + 0.5 \times 5.19 = 13.26 \text{m}^3/\text{s}$.

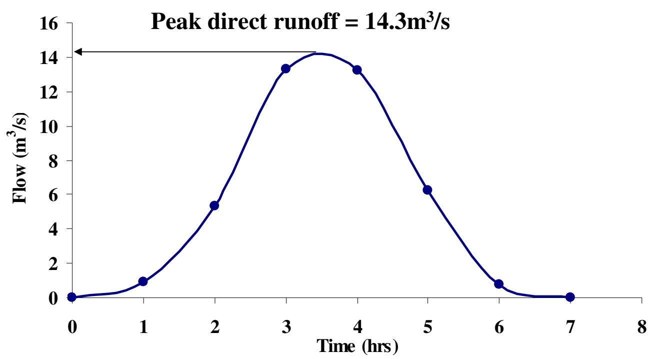
and so on……

Measuring the surface runoff

Result:

The watershed response as a runoff hydrograph due to the 3-hr storm.

Time (hrs)	Flow (m^3/s)
0	0
1	0.92
2	5.30
3	13.33
4	13.26
5	6.24
6	0.76
7	0



Measuring the surface runoff

Synthetic Unit Hydrograph:

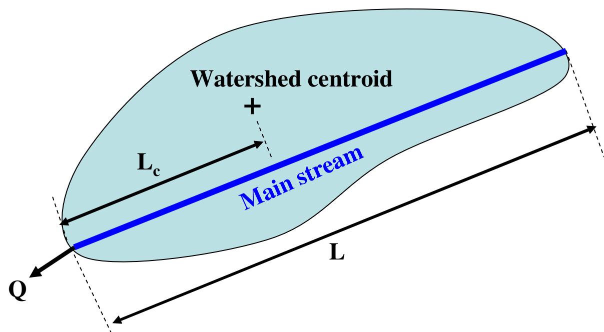
When the watershed has gauging stations to measure the actual *Q* resulted from given excess rainfall *P,* then the UH can be derived as shown previously. However, most of watersheds may not have gauging stations, therefore synthetic hydrographs is used to estimate the peak discharge.

Based on field observations, Snyder developed a methodology to derive the synthetic unit hydrograph based on the watershed characteristics like area, slope and the land cover.

Measuring the surface runoff

Snyder's synthetic Unit Hydrograph:

To develop the Snyder's synthetic unit hydrograph, five inputs are required: watershed area (A), the length of the main stream from outlet to divide (L), the length to the centroid of the basin (L_c), and two coefficients (C_t and C_p).



Measuring the surface runoff

Snyder's synthetic Unit Hydrograph:

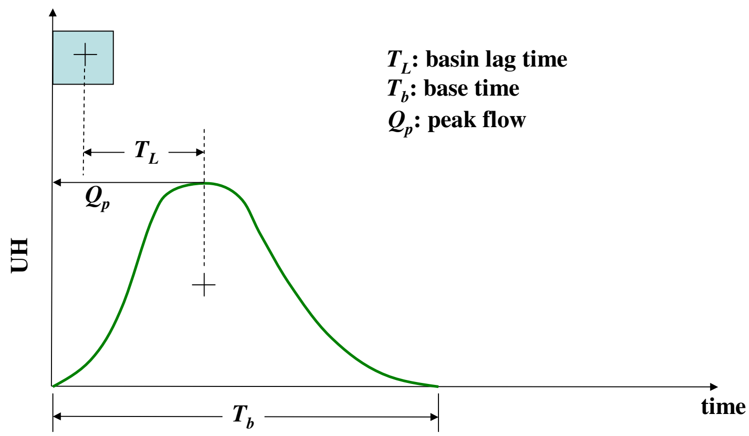
Snuder developed equations (models) to measure the time and peak flow based on ***observations*** and such models need corrections. The coefficients C_t and C_p are corrections for the time and the amount of peak flow.

Generally, typical values for C_t ranges from 0.3 – 6, while for C_p ranges from 0.31 – 0.93.

In practice: think how can you estimate C_t and C_p for a given watershed ??????

Measuring the surface runoff

Snyder's synthetic Unit Hydrograph: definitions.



Measuring the surface runoff

Procedure to derive the Snyder's UH:

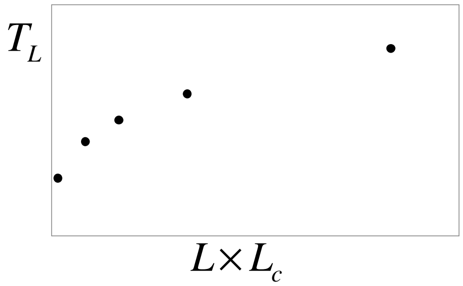
The basin lag: time from the centroid of the excess rainfall to the centroid of the hydrograph is:

$$T_L = C_t (L \times L_c)^{0.3}$$ T_L (hr), L & L_c (km)

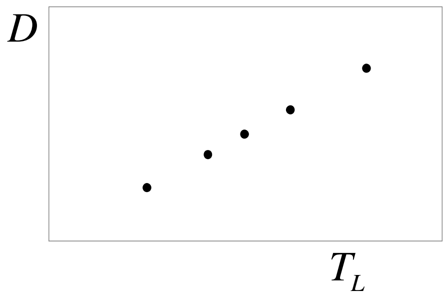
The duration of the excess rainfall is:

$$D = \frac{T_L}{5.5}$$ D (hr)

Measuring the surface runoff



$$\longrightarrow T_L = C_t (L \times L_c)^{0.3}$$



$$\longrightarrow D = \frac{T_L}{5.5}$$

Measuring the surface runoff

Procedure to derive the Snyder’s UH:

Adjusting the basin lag to correspond the desired rainfall time (D'):

$$T'_L = T_L + 0.25(D' - D)$$

The UH base time is:

$$T_b = 3 + \frac{T'_L}{8}$$ T_b (day), T_L (hr)

the equation above is used for relatively large basins, for small basins, use T_b (hr) = $4T_L$.

Measuring the surface runoff

Procedure to derive the Snyder's UH:

The peak direct runoff is:

$$Q_p = \frac{2.78 C_p A}{T_L'} \qquad Q_p \text{ (m}^3\text{/s)}, T_L \text{ (hr)}$$

The time to peak flow occurrence is:

$$T_p = \frac{D'}{2} + T_L'$$

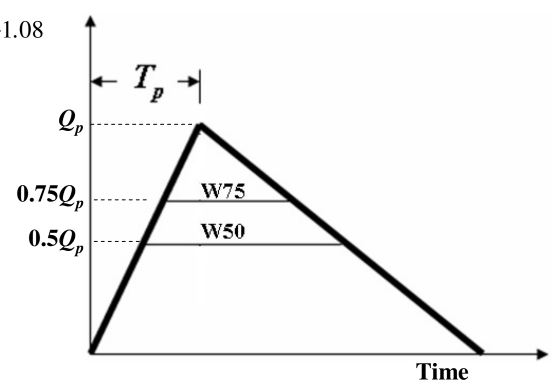
Measuring the surface runoff

Procedure to derive the Snyder's UH:

To assist in drawing the UH, compute W50 and W75 that are hydrograph time widths at 50 and 75% of the peak flow.

$$W50 = 5.87 \left(Q_p / A\right)^{-1.08}$$

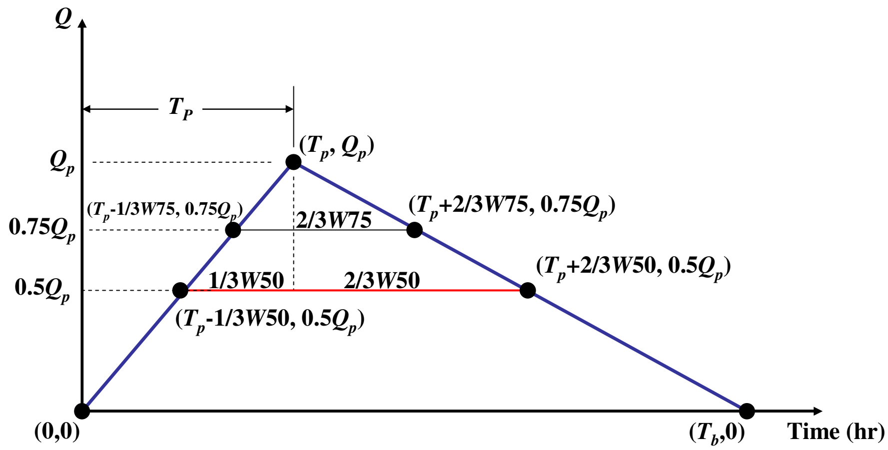
$$W75 = \frac{W50}{1.75}$$



Measuring the surface runoff

Procedure to derive the Snyder's UH:

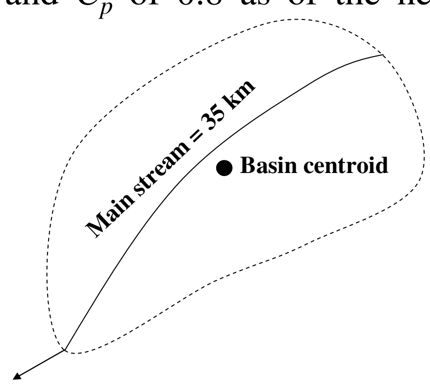
On the UH seven points will be available.



Measuring the surface runoff

Ex on Snyder's UH:

Develop a 2-hr unit hydrograph for the watershed shown. The basin area is 280km^2, and the distance along the main stream to the basin centroid nearest point is 20km. Use C_t of 1.5, and C_p of 0.8 as of the nearest gauged basin.



Measuring the surface runoff

Soln:

The basin lag is $T_L = C_t\left(L \times L_c\right)^{0.3} = 1.5(35 \times 20)^{0.3} = 10.7\,hrs$

The excess rainfall duration $D = \dfrac{T_L}{5.5} = \dfrac{10.7}{5.5} = 1.95\,hrs$

The desired UH is the 2-hr, so the excess rainfall is set at D' = 2 hrs, consequently the adjusted basin lag is:

$$T_L' = T_L + 0.25(D' - D) = 10.7 + 0.25(2 - 1.95) = 10.72\,hrs$$

and the UH base time is

$$T_b = 3 + \frac{T_L'}{8} = 3 + \frac{10.72}{8} = 4.34\,days = 104\,hrs$$

Measuring the surface runoff

Soln:

The peak runoff is

$$Q_p = \frac{2.78 C_p A}{T_L'} = \frac{2.78 \times 0.8 \times 280}{10.72} = 58.1 \ \text{m}^3/\text{s/cm}$$

The rise time (time to peak flow)

$$T_p = \frac{D'}{2} + T_L' = \frac{2}{2} + 10.72 = 11.72\,hrs$$

and $W50 = 5.87\left(Q_p / A\right)^{-1.08} = 5.87(58.1/280)^{-1.08} = 32.1\,hrs$

$$W75 = \frac{W50}{1.75} = \frac{32.1}{1.75} = 18.3\,hrs$$

Measuring the surface runoff

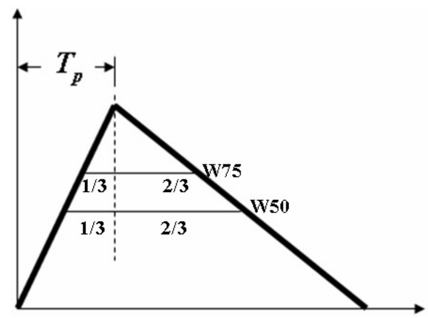
Soln:

the 1/3 of $W50 = 10.7hrs$, and the 2/3 of $W50 = 21.4hrs$

the 1/3 of $W75 = 6.1hrs$, and the 2/3 of $W75 = 12.2hrs$

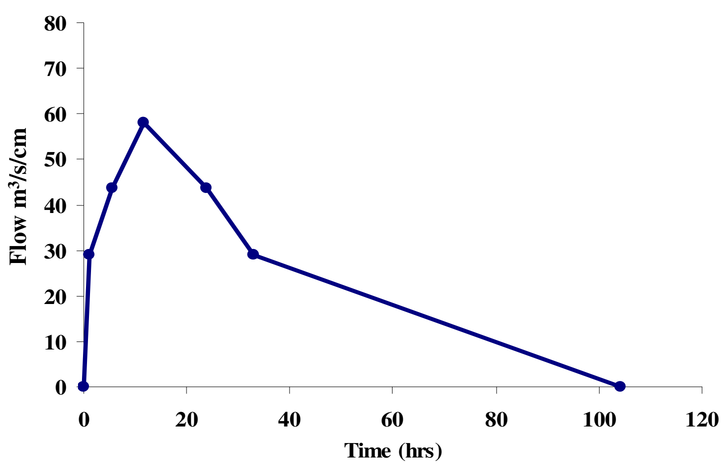
$T_p = 11.72\ hrs.$

Time (hrs)	Runoff ($m^3/s/cm$)
0.00	0
1.02	29.05
5.62	43.57
11.72	58.1
23.92	43.57
33.12	29.05
104.20	0



Measuring the surface runoff

The Snyder's synthetic 2-hr unit hydrograph:



Engineering Hydrology

110401454

Groundwater Hydrology

Instructor: Dr. Zeyad Tarawneh

Groundwater hydrology

Groundwater is part of the total water that is entrapped by impermeable layers called ***aquicludes***. Such aquicludes form the shape of the groundwater container (***aquifer***). While part of the groundwater may be rechargeable due to infiltration, other part is un-rechargeable.

The groundwater hydrology cares generally about studying the aquifers properties, groundwater movements, groundwater flow amount, and the drop in the groundwater table (drop in storage).

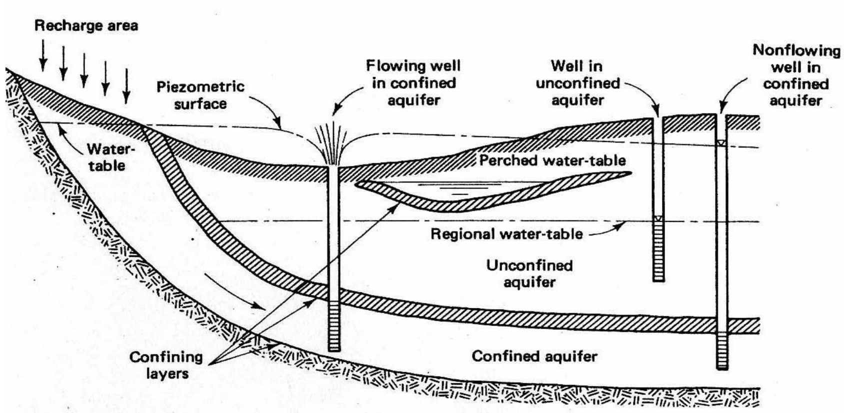
Groundwater hydrology

Groundwater ***aquifers*** are geological formations with sufficient permeability to allow the groundwater extraction (pumping out). In nature, such aquifers are either ***confined*** or ***unconfined***.

The ***confined aquifer*** is geological layer that is entrapped by two less permeable layers (two aquicludes) and the water flows as in closed conduits (pressurized pipes), while the ***unconfined aquifer*** has an upper saturated permeable layer with defined water table. The flow regime in such aquifer is similar to flow in open channels.

Groundwater hydrology

Types of aquifers



Types of aquifers.

Groundwater hydrology

The groundwater flow:

The groundwater flow characteristics depend on the permeability of the conveyance medium, and the hydraulic gradient (water head difference). The groundwater flow velocity is directly related to the hydraulic gradient within the aquifer. Darcy expressed the velocity as:

$$V = -k \frac{\partial h}{\partial r} = -k\, s$$

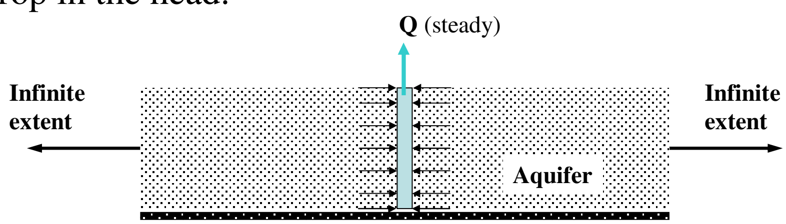
k: constant called the hydraulic conductivity,
∂h: drop in hydraulic grade line between 2 observation points,
∂r: horizontal distance between 2 observation points,
s: the hydraulic gradient.

Groundwater hydrology

Equilibrium analysis of the groundwater flow:

The equilibrium analysis to solve the Darcy equation assumes that:

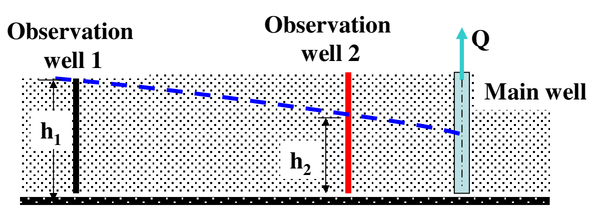
- the flow rate from the aquifer is constant (*steady*),
- the well is screened through the entire aquifer depth,
- the aquifer is uniform of infinite extent (Isotropic),
- the water is released immediately in response to a drop in the head.



Groundwater hydrology

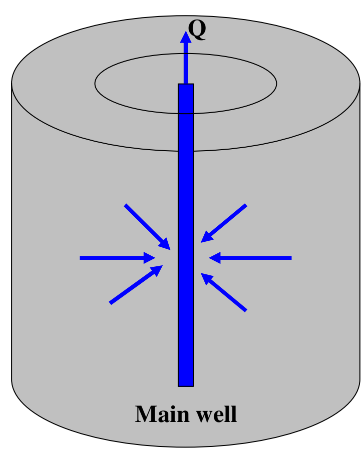
Observation wells:

To study the flow from the main groundwater well, an observation wells are introduced. The purpose of the observation well is to control the operation of the main well through supplying groundwater measurements.



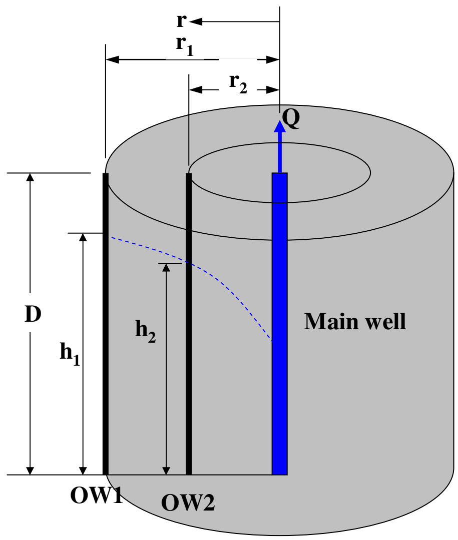
Groundwater hydrology

The groundwater is assumed to move towards the main well from all horizontal directions (steady radial flow).



Groundwater hydrology

Steady radial flow:



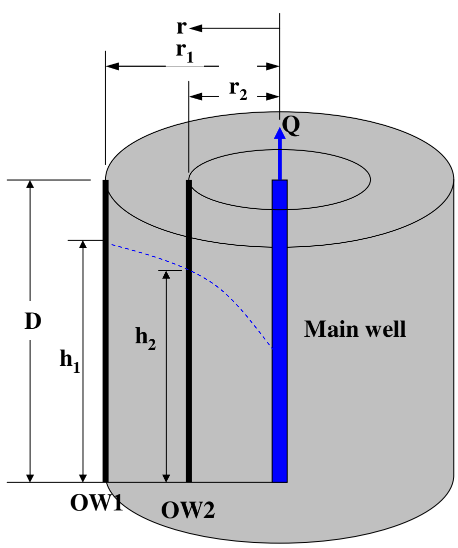
$$V = k\frac{dh}{dr}$$

$$Q = k\frac{dh}{dr}A$$

$$Q = k\frac{dh}{dr}(2\pi r D)$$

Groundwater hydrology

Steady radial flow:



$$Q = k\frac{dh}{dr}(2\pi r D)$$

$$\frac{dr}{r} = \frac{2\pi D k}{Q}dh$$

$$\int_{r_1}^{r_2}\frac{dr}{r} = \frac{2\pi D k}{Q}\int_{h_1}^{h_2} dh$$

Groundwater hydrology

Steady radial flow:

$$\int_{r_1}^{r_2} \frac{dr}{r} = \frac{2\pi Dk}{Q} \int_{h_1}^{h_2} dh$$

Check what will happen if the equilibrium analysis assumptions are not applicable

$$\ln(r_2) - \ln(r_1) = \frac{2\pi Dk}{Q}(h_2 - h_1)$$

Groundwater hydrology

Steady flow from the confined aquifer:

Solving the Darcy equation and using the simplifications stated through the assumptions of the equilibrium analysis, the groundwater flow rate from the confined aquifer of constant thickness *D* is:

$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\mathbf{ln}(r_2 / r_1)}$$

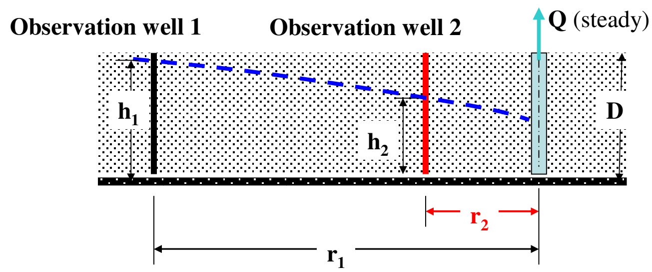
The term *kD* is called the aquifer transmissivity (*T*)
h_1 and h_2: the hydraulic water head at the observation wells 1 and 2,
r_1 and r_2: the radial distances to observation wells 1 and 2.

Groundwater hydrology

Steady flow from the confined aquifer :

$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\ln(r_2 / r_1)}$$

The distance *r* measured from the center line of the observation well to the centre line of the main well.



Groundwater hydrology

Steady flow from the unconfined aquifer:

In unconfined aquifers, the aquifer thickness *D* varies (not constant). If the thickness *D* is expressed in terms of the water head (*h*) that is measured from the underlying aquiclude (bottom layer), in that case the flow rate under the assumption of an equilibrium analysis is:

$$Q = \frac{2\pi k\left(h_2^2 - h_1^2\right)}{\ln(r_2 / r_1)}$$

Groundwater hydrology

Ex:

The flow from a main well in a confined aquifer of 15m thickness is 25L/s. If the water table elevations at two observations wells 50m and 20m away of the main well are 114.6m and 112.5m respectively, find the transmissivity of the aquifer?

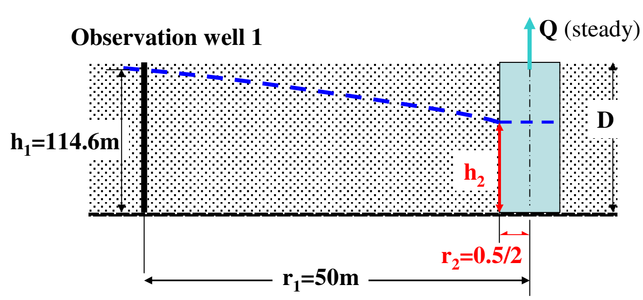
$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\ln(r_2 / r_1)} = 0.025 = \frac{2\pi k\,(15)(112.5 - 114.6)}{\ln(20/50)}$$

k = 10m/day, and T = 150m^2/day.

Groundwater hydrology

Ex:

A main well has diameter of 0.5m and transmissivity of 150m^2/day, what is the height of the water table head at the main well if the water head at an observation well 50m away is 114.6m?



Groundwater hydrology

Soln:

$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\mathbf{ln}(r_2 / r_1)} =$$

$$0.025 = \frac{2\pi(150/86400)(h_2 - 114.6)}{\ln(0.25/50)}$$

The water table head at the main well is h_2 = 102.5m

Groundwater hydrology

Self test question:

A main well of 0.5m diameter penetrates a confined aquifer of k = 20m/day and thickness of 35m. The flow is pumped from the main well such that its water table is maintained at drawdown (drop) of 5m below the water table of an observation well that is 600m from the main well, what is the discharge from the main well?

Groundwater hydrology

The hydraulic conductivity in anisotropic aquifers:

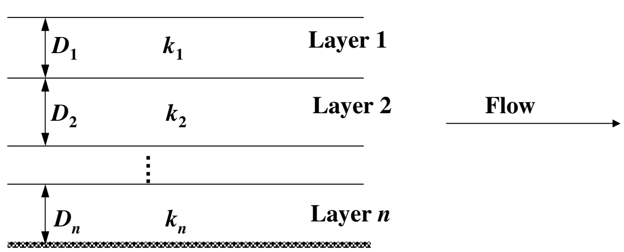
When the aquifer material varies either horizontally or vertically, then the aquifer is anisotropic and hence an average k should be used. This case is more realistic than assuming that the aquifer is totally isotropic (k is constant), however in reality, the aquifer contains materials that differ in properties in all directions.

To simplify the study in case of anisotropy, the variation in the k will be detailed in the horizontal and vertical direction.

Groundwater hydrology

The equivalent horizontal hydraulic conductivity:

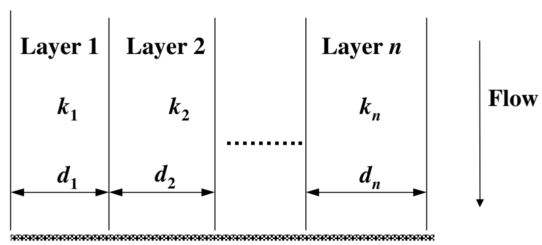
Assume an aquifer of horizontal layers 1, 2, ..,n.



$$k_H = \frac{k_1 D_1 + k_2 D_2 + \dots\dots + k_n D_n}{D_1 + D_2 + \dots\dots + D_n}$$

Groundwater hydrology

The equivalent vertical hydraulic conductivity:
Assume an aquifer of vertical layers 1, 2, ..,n.



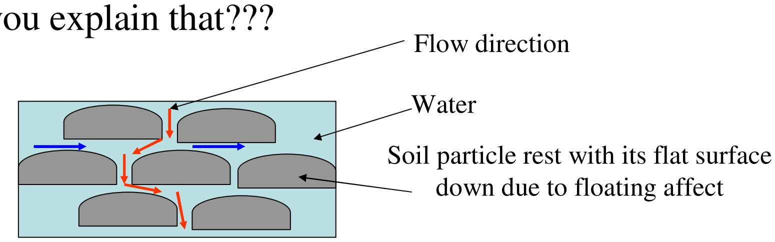
$$k_V = \frac{d_1 + d_2 + \ldots\ldots + d_n}{\frac{d_1}{k_1} + \frac{d_2}{k_2} + \ldots\ldots + \frac{d_n}{k_n}}$$

Groundwater hydrology

The relation between k_H and k_V:

In literature, it has been found that the horizontal hydraulic conductivity k_H is always greater than the vertical hydraulic conductivity k_V ($k_H / k_V \approx 2 - 10$). For clay soils the ratio may reach up to 100.

Can you explain that???



Drop in the groundwater table

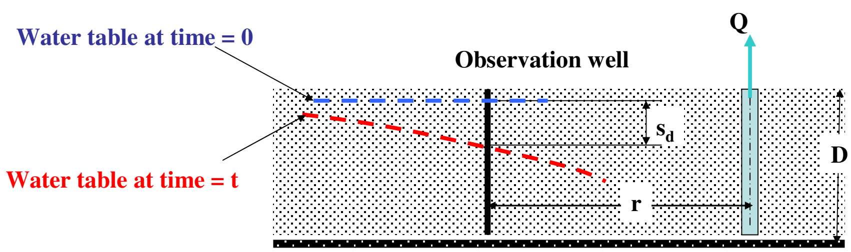
Nonequilibrium analysis:

For the case of the non-equilibrium analysis and given the flow rate, then the drop in hydraulic head (drop in the water table level) is expressed by the Cooper-Jacob approximation as (s_d):

$$s_d = \frac{Q}{4\pi T}\ln\left(\frac{2.25T\,t}{r^2\,S}\right)$$

s_d : the drop in water table (m),
t : the time (seconds),
r : distance between the main and the observation well
S: volume released per unit volume of the aquifer per unit drop in the water table (unit less).

Drop in the groundwater table



$$s_d = \frac{Q}{4\pi T}\ln\left(\frac{2.25T\,t}{r^2\,S}\right)$$

Drop in the groundwater table

Ex:

An aquifer of T = 150m^2/day, $S = 10^{-4}$ provides flow of 25L/s to a main well. Find the drop (s_d) at an observation well 20m away from the main well after 1day and 30days of pumping?

Soln: Applying the Cooper-Jacob approximation for s_d then:

$$s_d = \frac{Q}{4\pi T}\mathbf{ln}\left(\frac{2.25T\,t}{r^2\,S}\right)$$

$$s_d = \frac{0.025}{4\pi\left(\frac{150}{86400}\right)}\ln\left(\frac{2.25(150)t}{(20)^2\times10^{-4}}\right)$$

Drop in the groundwater table

Substituting 1day and 30days for t in the equation (s_d), the results are shown below:

t (days)	s_d (m)
1	10.36
30	14.26

What do you observe?

Drop in the groundwater table

Ex:

A confined well produces flow through an aquifer of T = 200m^2/day. The volume released per unit volume of aquifer per unit drop in the water table is 0.008. Calculate the 2 days drop at an observation well 40m away from the main well when the flow for the first day is 100L/s while for the second day is 80L/s. ?

Soln: Applying the Cooper-Jacob approximation for s_d then:

$$s_d = \frac{Q}{4\pi T}\mathbf{ln}\left(\frac{2.25T\,t}{r^2\,S}\right)$$

Drop in the groundwater table

The drop for the first day at Q of 100L/s =

$$s_d = \frac{0.1}{4\pi(200/86400)}\ln\left(\frac{2.25(200)(1)}{(40)^2(0.008)}\right) = 12.238m$$

The drop for the second day at Q of 80L/s =

= s_d at Q of 80L/s for t = 2 days – s_d at Q of 80L/s for t = 1day

$$= \frac{0.08}{4\pi(200/86400)}\ln\left(\frac{2.25(200)(2)}{(40)^2(0.008)}\right) - \frac{0.08}{4\pi(200/86400)}\ln\left(\frac{2.25(200)(1)}{(40)^2(0.008)}\right) = 1.906m$$

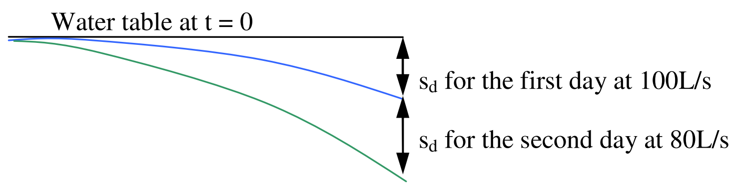
Drop in the groundwater table

The total (cumulative) drop over the whole 2 days =

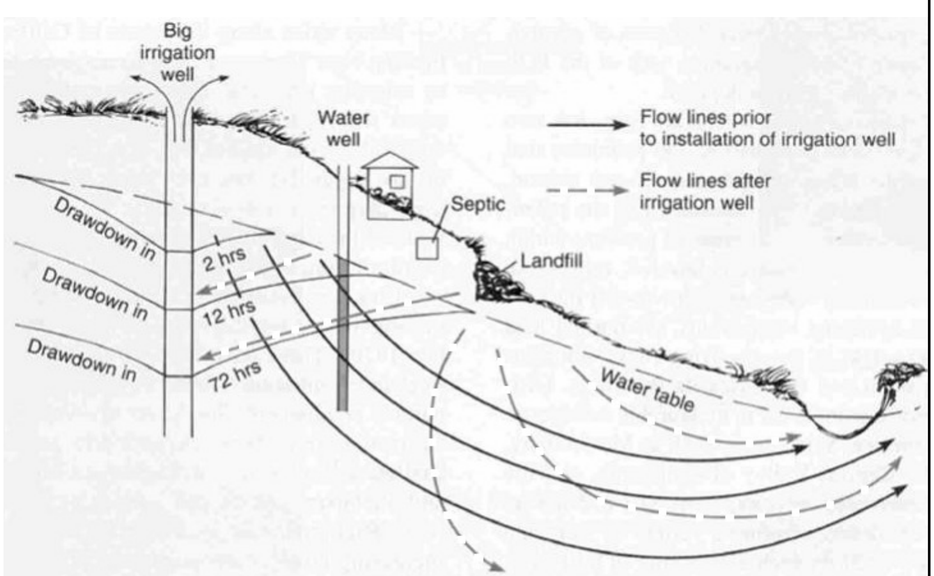
= s_d at 100L/s for the first day + s_d at 80L/s for the second day

= 12.238 + 1.906

= 14.144m



Drop in the groundwater table



Drop in the groundwater table

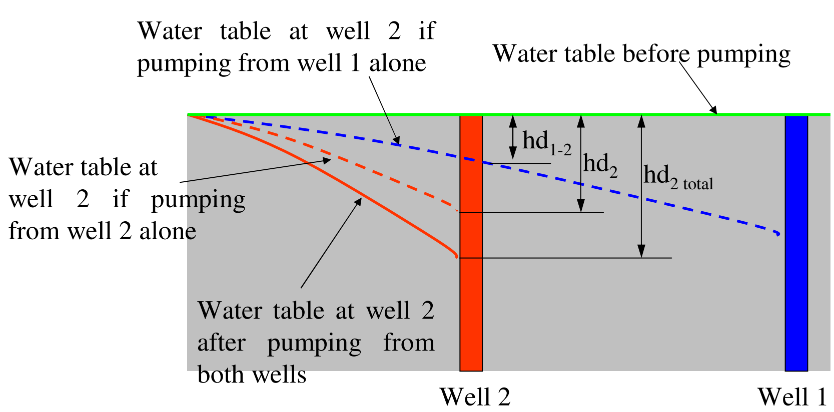
Multiple well system:

When there are multiple active wells in the same aquifer, then pumping from individual wells will add cumulative effect (multiple wells together) on the groundwater table, i.e. each well will affect (drop) the water head at other wells. In reality, a minimum distance between active wells is kept to reduce such effect, such distance is called the well influence distance.

The well influence distance is defined as the radial distance from the well center such that the water table drop is kept nearly zero!!! when the well is under operation.

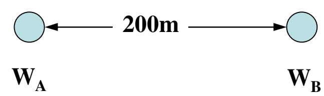
Drop in the groundwater table

Observe the effect of well 1 on well 2 just.



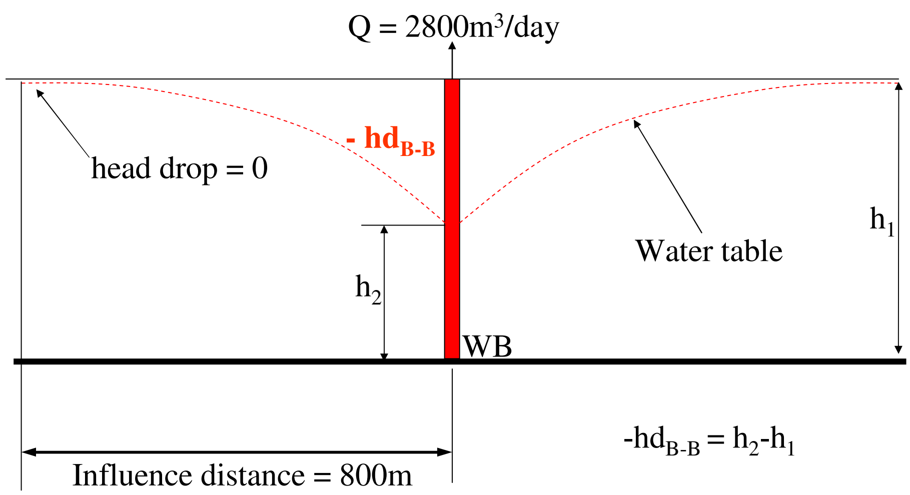
Drop in groundwater level

Ex:
Two pumping wells in confined aquifer with 800m influence distance are located as shown. Water is pumped from well B at steady rate of 2800m^3/day, calculate the steady state flow from well A such that the total head drop at well B not to exceed 2m when *T* is 2400m^2/d. Well B has 40cm diameter.



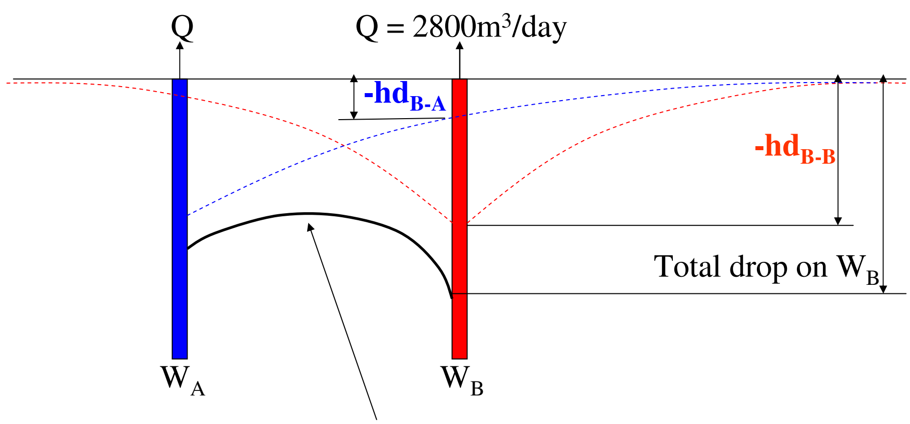
Drop in groundwater level

Head drop at well B from its self (hd_{B-B}).



Drop in groundwater level

Influence on well B from its self and from well A.



Drop in groundwater level

Soln:
T = 2400/86400 = 0.0278m^2/s. Q_2 = 2800m^3/d = 0.032m^3/s.

The total head drop at W_B = head drop at W_B from W_B (hd_{B-B}) + head drop at W_B from W_A (hd_{B-A}) ≤ - 2m.

$-hd_{B-B} + (-hd_{B-A}) \leq -2$m.

The drop on W_B from its self (hd_{B-B}) is estimated from:

$$Q = \frac{2\pi T(h_2 - h_1)}{\ln(r_2 / r_1)}$$

$$Q_B = \frac{2\pi \times 0.0278(-hd_{B-B})}{\ln(800/0.2)} = 0.032 \longrightarrow hd_{B-B} = 1.52\text{m}$$

Drop in groundwater level

Soln:
The drop on W_B from W_A is $hd_{B\text{-}A}$ that can be computed from: $-hd_{B\text{-}B} + (-hd_{B\text{-}A}) \leq -2m$.

Given $hd_{B\text{-}B} = 1.52m$, then $hd_{B\text{-}A} \leq 0.48m$.

$$Q = \frac{2\pi T(h_2 - h_1)}{\ln(r_2 / r_1)}$$

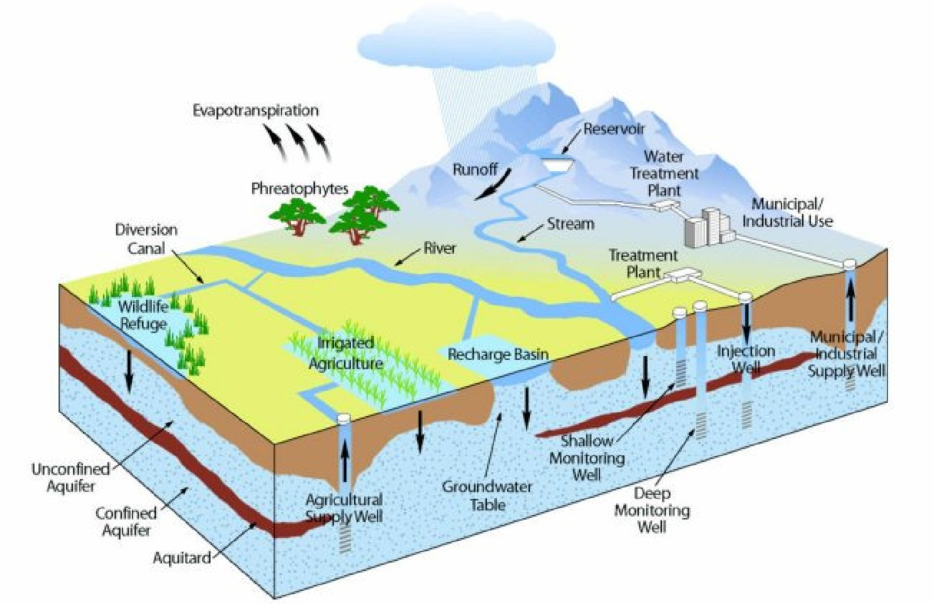
$$Q_A = \frac{2\pi \times 0.0278(-hd_{B-A})}{\ln(800/200)} =$$

$$Q_A = \frac{2\pi \times 0.0278(-0.48)}{\ln(800/200)} = 0.06m^3/s \qquad = 5223m^3/day$$

Groundwater artificial recharge

Definition:
The term groundwater artificial recharge refers to the process of transferring the surface water to the groundwater aquifer by human interference. The main concept behind the artificial recharge is to construct simple structures to entrap surface water that will be eventually transferred to the groundwater after being infiltrated through the soil layers. Therefore, the recharge process depends on the quantity of the surface water stored and the soil properties as well (fast versus slow artificial recharge will depend on the soil void ratio, soil particle size, soil moisture content).

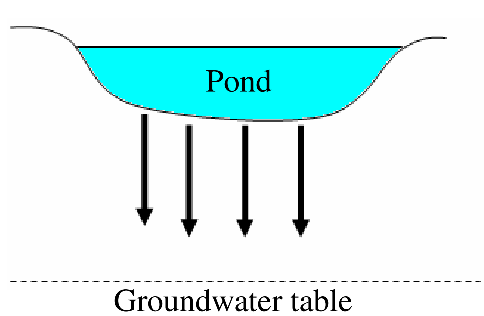
Groundwater artificial recharge



Groundwater artificial recharge

Techniques of artificial recharge:

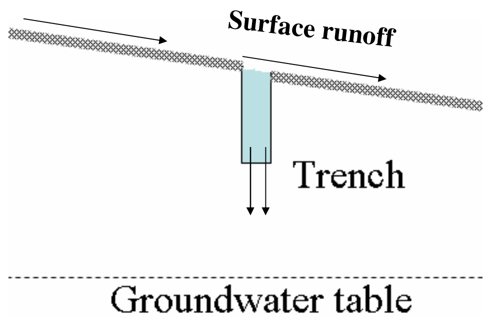
- Infiltration pond (recharge basin): are natural soil ponds placed next to major surface runoff streams to store surface water and allow the infiltration through soil to the underlying unconfined aquifer.



Groundwater artificial recharge

Techniques of artificial recharge:

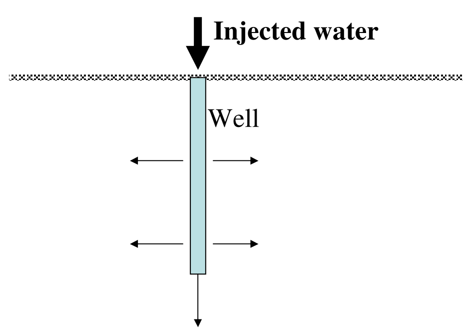
- Trenches: are structures in natural soil placed sloppy lands to intercept surface runoff and store water and allow the infiltration through soil to the underlying unconfined aquifer.



Groundwater artificial recharge

Techniques of artificial recharge:

- Injection wells: are structures similar to bore wells where surface water is pressure or gravity injected to supply water to ground aquifers.



Groundwater artificial recharge

Advantages of artificial recharge:

- It utilizes the surplus surface water to enhance the groundwater storage and eventually increases the safe yield.
- It requires simple and low cost structures to store water for recharge.
- It has negligible losses (no evaporation).
- It improves the groundwater quality through diluting potential groundwater solids content.

Groundwater artificial recharge

Ex:
Observe the recharge % of the total annual inflow for the Wala dam reservoir.

Year	Total inflow (m^3)	Spilling (m^3)	Recharged water (m^3)	%
2008	1,349,793	------	1,220,721	90
2009	16,381,583	6,754,228	8,777,947	54
2010	34,570,535	25,173,738	9,617,735	28
2011	3,223,646	------	2,145,678	67

Introduction to water resources

The science of water resources is the water science that focuses on studying the availability of water stored in a region to cover the demand on water for human activities like the domestic need (drinking, cooking and cleaning), industrial activities need (food industry, paper industry, tanning industry, structure industry, etc), agricultural activities need, and recreational activities need.

In general water is available from the following sources: <u>surface water</u> (rivers, springs, natural and artificial lakes), groundwater aquifers, treated wastewater, and fresh water production using membrane filtration.

Water resources classification

All water resources are classified either **traditional** or **non-traditional** water sources. Traditional water sources are those evolved due to natural events like precipitation or snow-melt (no human interference) like flow in rivers and natural lakes. By definition, all groundwater sources are traditional sources.

On the other hand, the non-traditional water resources are those evolved due to human interference (man-made structures) like treated wastewater from treatment plants, and the freshwater production from desalting seawater and brackish water using membrane filtration. In Jordan, water from both traditional and non-traditional sources is available.

Water resources classification

It should be noted that all the **non-traditional** water resources are renewable resources, for example the fresh water production from seawater desalination projects (imagine the size of seas and oceans).

As a traditional water source, while part of the groundwater sources is considered renewable, other part is considered non-renewable sources (for example, the Disi aquifer is a non-renewable groundwater source).

Surface water sources from rivers, greeks, natural and artificial lakes and from the snowmelt are renewable water sources, however water amounts that can be utilized depend on the precipitation amount and the amount of water withdrawn.

Water resources facts (worldwide)

Table 1. Annual renewable water per person

	Renewable annual freshwater available (m^3/person)	Rank
Water-scarce countries (20 countries)		
Jordan	327	10
Water-stressed countries (8 countries)		
Egypt	1 123	23
Cyprus	1 282	25
Water-abundant countries		
Lebanon	1 818	31
Syria	2 087	36
Turkey	3 626	61
United States	9 913	91
Canada	108 900	141

The study is based on 149 countries worldwide.

Utilized water resources in Jordan

The following table shows the distribution of the annual amounts of water that can be utilized from different sources in Jordan:

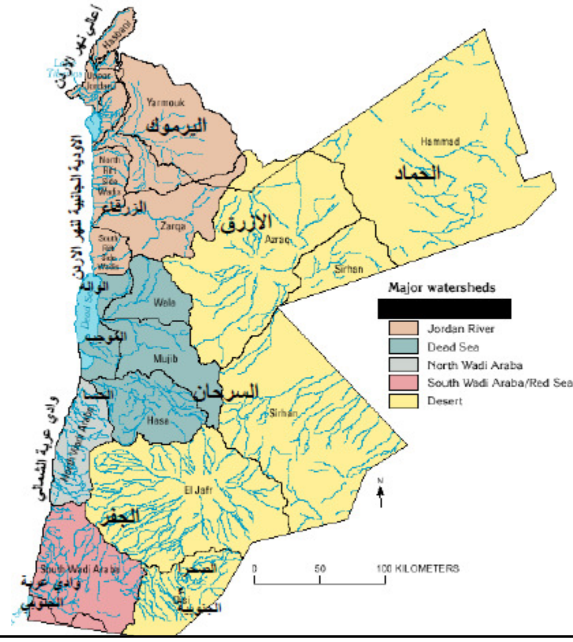
Source	amount (Mm^3)
Renewable groundwater	280
Non-renewable groundwater	140
Surface water	750
Treated wastewater	100
Brackish water (ready for desalting)	70

Surface water in Jordan

An other primary source of water in Jordan is the surface water from surface basins (large area that contributes surface water). The following table refers to major surface basins in Jordan.

Basin	annual surface water flow (Mm^3)
Yarmouk river basin	166
Zarqa river basin	84
Mujib & Wala basin	102
Dead sea side wadis	43
Hesa	43
Jafr	13
Azraq	41
Northern wadi araba	46

Surface basins in Jordan



Distribution of water usage in Jordan

Water from different sources in Jordan is used mainly to cover the needs of domestic purposes, agriculture and industrial activities. The following table shows the distribution of water usage in Jordan for the year 2005 versus competing sectors.

Sector	amount used (Mm^3/yr)	% of water use
Domestic	291	31
Agriculture	604	64
Industrial	38	4
Live-stock	8	1
Total	941	100

The stressed water resources in Jordan

Due to the limited water resources in Jordan, the increased demand on water for domestic, agriculture and industrial activities has exceeded the available water sources. The following table shows future scenarios about the demand versus the supply in Jordan.

Year	Total demand (Mm^3)	Total supply (Mm^3)	Deficit (Mm^3)
2010	1383	1054	329
2020	1602	1152	450
2040	2236	1549	687

Introduction to surface water resources

Surface water resources in Jordan contribute about 38% of the national water balance. The majority of the surface water in Jordan comes from winter floods collected in major dams and stream flows from the Yarmouk river, Zarqa river and other eastern tributaries (Wadis) of the lower Jordan river.

Such water source is considered renewable, however surface water sources in Jordan are exploited due lack of precipitation in recent years and the increased demand on water.

From water quality perspective, surface water needs further treatment for domestic purposes when compared to groundwater sources (why?).

Surface water usage

Surface water resources in Jordan are used for different purposes including:

1. Water supply for irrigation use, mainly in the Jordan valley (about 30000 hectares) and highlands (about 4000 hectares).
2. Water supply for domestic use (Zai water treatment plant is provided by water from Eastren Ghor Canal).
3. Water source for industry (Potash Arab Co. is supplied partially by its water needs from the Mujib dam).
4. Hydro-power generation (King Talal dam).
5. Groundwater recharge (Wala dam, Sewaqa dam).

Surface water resources

Major rivers and wadis in Jordan.

River	**Basin area (Km^2)**	**Average historic annual flow (Mm^3)**	**Water utilized (Mm^3)**
Jordan	18194	1400	----
Yarmouk	6974	440 (reduced to 360)	100
Zarqa	4154	85	Fully utilized
Wadi El-Arab	246	28	Fully utilized
Wadi Ziglab	100	10	Fully utilized
Wadi Kafrain	159	17	Fully utilized
Wadi Mujib	4380	83	Fully utilized

Surface water resources

As can be seen from the previous table, the Yarmouk river is considered as the main, the largest, and the most important surface water resource in Jordan and considered as a vital national resource. Recall that the Yarmouk river is multi-share sources (Jordan about 100Mm^3, Syria about 160Mm^3, and others about 100Mm^3).

It should be noted that Jordan cannot use the water from Jordan river. The river natural freshwater flow has been interrupted and abstracted before reaching Jordanian lands, where only return irrigation flow and saline water remains.

Surface water resources

Major reservoirs in Jordan.

Dam	**Catchment area (Km^2)**	**Live storage (Mm^3)**	**Purposes**	**Water resources**
Wadi El-Arab	262	17	Irrigation, domestic water supply, power generation.	King Abdullah Canal in winter and floods of Wadi El-Arab.
King Talal	3,700	75	Irrigation, power generation.	Zarqa River and As-Samra wastewater treatment plant.
Al Karameh	61	55	Irrigation.	Surplus water from King Abdullah Canal in winter.
Kafrein	163	9	Irrigation, artificial recharge.	Flood and base flow from wadi Kafrein.

Surface water resources

Major reservoirs in Jordan.

Dam	**Catchment area (Km^2)**	**Storage (Mm^3)**	**Purposes**	**Water resources**
Wehdah	6974	100	Irrigation, domestic water supply.	Yarmouk river flow, winter flood.
Mujib	4380	32	Irrigation, domestic and industrial water supply.	Mujib valley springs, winter flood.
Al tannur	2160	16	Irrigation.	Hesa valley springs, winter flood.
Wala	1770	9	Irrigation, domestic and industrial water supply, groundwater recharge.	Winter flood.

In addition to major dams, there are 18 micro-dam of $31Mm^3$ total capacity, the largest among are Rowyshed dam of $10Mm^3$, Bayer dam of $5Mm^3$, and Qatraneh dam of $4.2Mm^3$.

Surface water resources

Mujib dam reservoir in Jordan.

Surface water resources

Winter flood at spillway of Wala dam.

Surface water storage

Reservoirs:

Reservoirs are large artificial lakes created by barriers (dams) to entrap surface water from natural streams to store and release water when needed. Reservoirs are classified according to the purpose into single-purpose reservoirs (Al Karameh dam reservoir for irrigation) and multi-purpose reservoirs (King Talal dam reservoir for irrigation and power generation).

Two major issues related to reservoirs are: to estimate the current storage capacity of existed reservoir, and to estimate the required capacity to meet future needs of water.

Surface water storage

Reservoir purposes:

Reservoirs are built to store and release water for several purposes including:

- Supply fresh water for domestic use,
- Supply water for irrigation,
- Flood control,
- Hydropower generation,
- Recreational purpose, and
- Creating positive impact on the environment.

Surface water storage

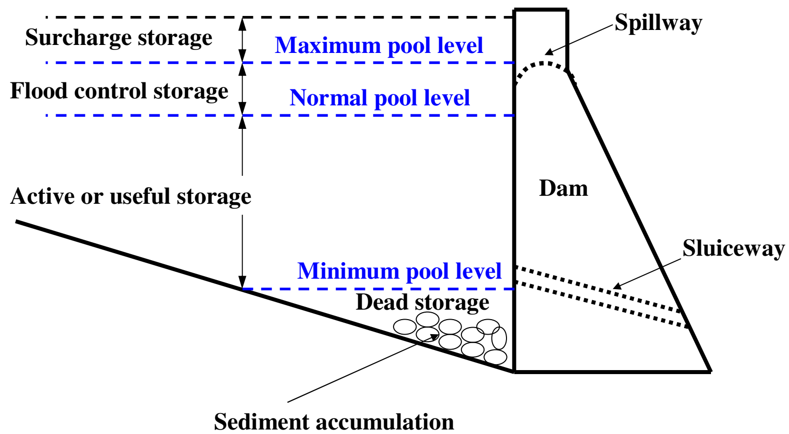
Reservoir storage components:

Reservoir storage consists of following components:

- Normal pool level,
- Minimum pool level,
- Active or useful storage,
- Dead storage,
- Surcharge storage, and
- Flood control storage.

Surface water storage

Reservoir storage components:



Surface water storage

Reservoir storage yield:

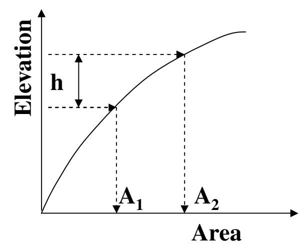
- Yield from a reservoir: the water amount that can be withdrawn from a reservoir in a specified period of time.
- Safe yield (firm yield): the maximum water volume can be supplied in a specified period of time during critical period (dry season).
- Secondary yield: the water volume that is available during high inflow season.

Surface water storage

Storage capacity of existed reservoir:

The trapezoidal formula is one of several methods used to estimate the current storage capacity of existed reservoir. It simply relies on estimating the water surface area from elevation-area curves (contour areas at h contour interval) and then the volume of water stored between two contours (surface areas A_1 and A_2) is given as:

$$\Delta V_1 = \frac{h}{2}(A_1 + A_2)$$



Surface water storage

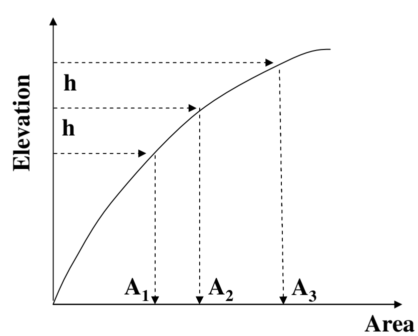
Storage capacity of existed reservoir:

The total storage volume (V) is the sum of sub-volumes between contour areas:

$$\Delta V_1 = \frac{h}{2}(A_1 + A_2)$$

$$\Delta V_2 = \frac{h}{2}(A_2 + A_3)$$

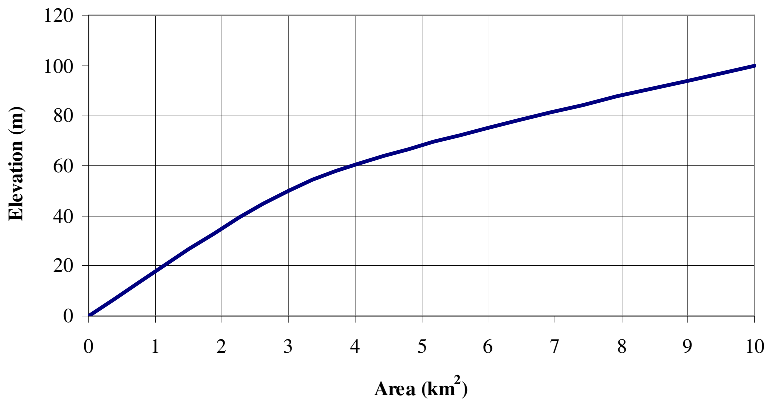
$$V = \Delta V_1 + \Delta V_2 + \ldots.$$



Surface water storage

Ex:

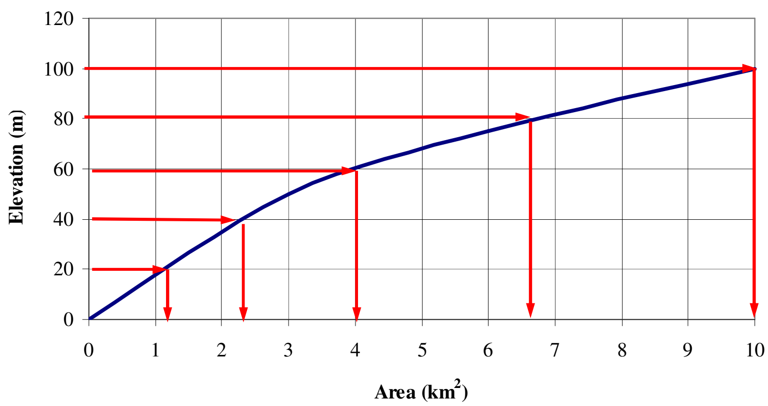
From the given elevation-area curve find the total storage volume (V) of an existed reservoir.



Surface water storage

Soln:

To compute the total storage volume (V) of the existed reservoir, contour interval of 20 is selected. At elevation 0m the area A_1 is 0km2, at 20m A_2 is 1.2km^2, at 40m A_3 is 2.3km^2, and so on..



Surface water storage

Soln:

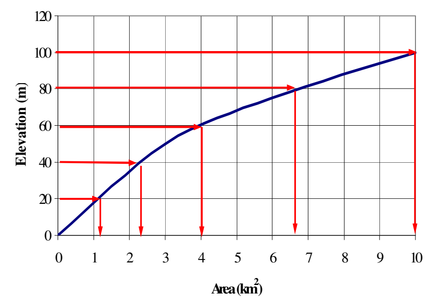
$$V = \Delta V_1 + \Delta V_2 + ...$$

$$V = \frac{20}{2}(0+1.2)+\frac{20}{2}(1.2+2.3)+\frac{20}{2}(2.3+4)$$

$$+\frac{20}{2}(4+6.7)+\frac{20}{2}(6.7+10)$$

$$= 384 m.km^2$$

$$= 384 Mm^3$$



Surface water storage

Storage capacity determination:

The storage capacity determination for non-existed reservoir is an important key for well managing water resources systems. The storage capacity is function of two elements: the inflow water amount (supply) and the outflow amount (demand or release).

In the next few slides, the active storage or the useful storage capacity will be determined. The size of the active storage highly relies on dry period analysis (critical period).

Surface water storage

Storage capacity determination:

In literature, the active storage capacity of reservoirs is determined using four methods:

1- The mass curve method (Ripple method).

2- Sequent peak method (analytical method) .

3- Operation approach.

4- Optimization approach.

For the purpose of this course, the first two methods will be discussed.

Surface water storage

Storage capacity determination:

The mass curve method (Ripple method) is used to estimate the active storage capacity of reservoirs when the demand on water (release) is constant. In the mass curve, the cumulative inflow determines the total supply, while the cumulative constant demand represents the total withdrawn. Our target is to maintain storage for the incoming flows during wet periods to overcome the largest deficit between the demand and the little inflow (little supply) during the dry periods.

The following example will show detailed solution.

Surface water storage

Ex:

Use the mass curve method (Ripple method) to estimate the active storage capacity of a reservoir that will be installed on a river with yearly inflows as shown in the table to overcome a constant demand on water of 70000m^3/yr.

Year	Inflow (m^3/yr)
2000	60000
2001	126000
2002	19000
2003	28000
2004	107000
2005	140000
2006	66000
2007	14000
2008	40000
2009	149000
2010	51000

Surface water storage

Soln:

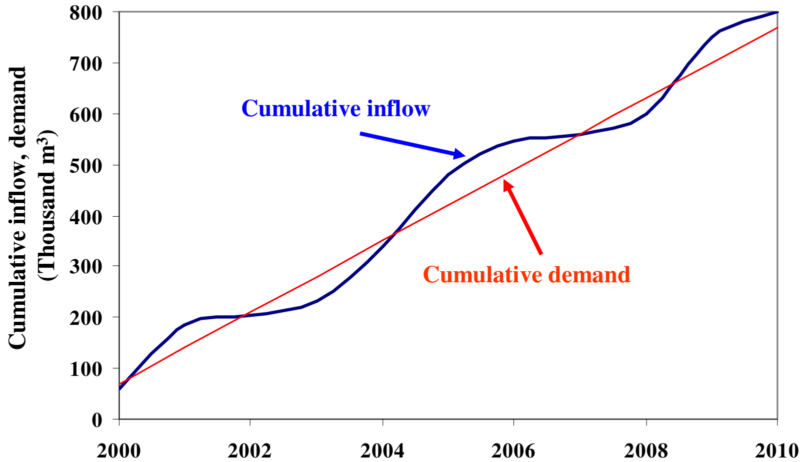
Step1: Calculate the cumulative inflows and cumulative demand.

Year	Inflow m^3	Cumulative inflow m^3	Demand m^3	Cumulative demand m^3
2000	60000	60000	70000	70000
2001	126000	186000	70000	140000
2002	19000 +	205000	70000	210000
2003	28000	233000	70000 +	280000
2004	107000	340000	70000	350000
2005	140000	480000	70000	420000
2006	66000	546000	70000	490000
2007	14000	560000	70000	560000
2008	40000	600000	70000	630000
2009	149000	749000	70000	700000
2010	51000	800000	70000	770000

Surface water storage

Soln:

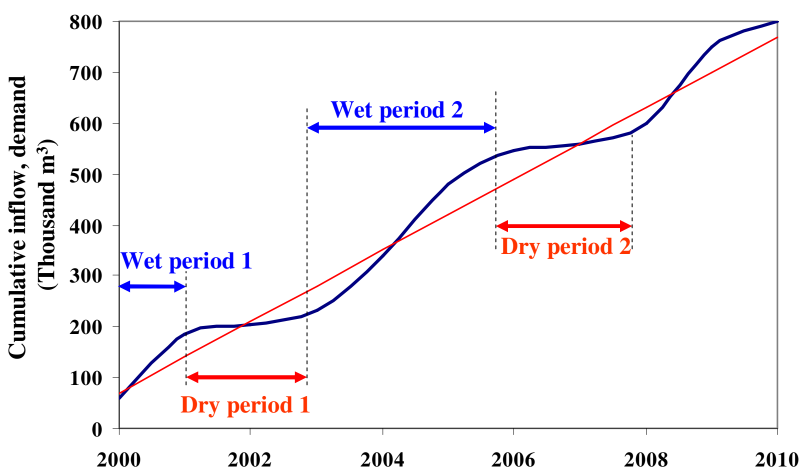
Step2: Plot the cumulative inflows and cumulative demand.



Surface water storage

Soln:

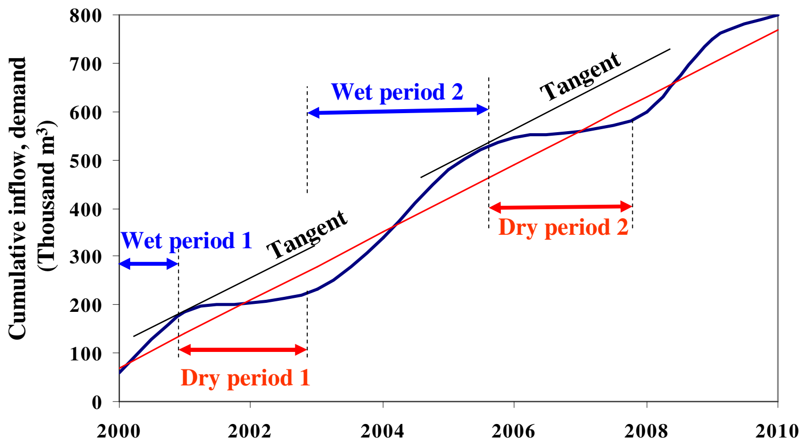
Step3: Locate dry and wet periods.



Surface water storage

Soln:

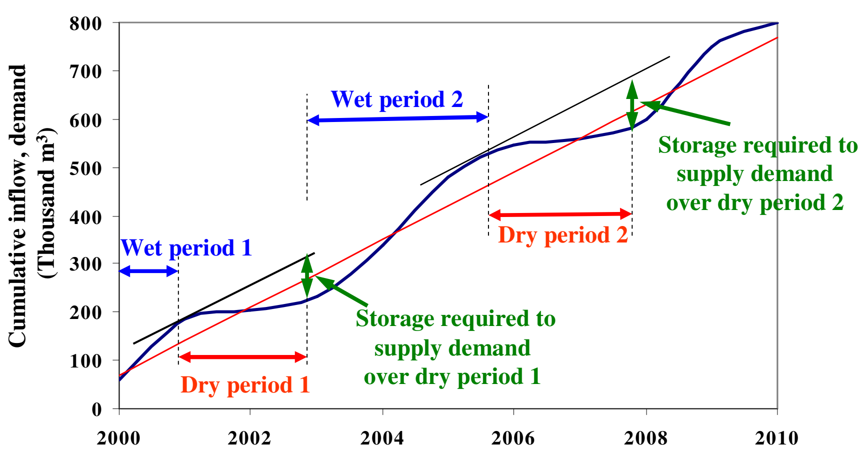
Step4: Construct tangents (parallel to demand) at the beginning of dry periods.



Surface water storage

Soln:

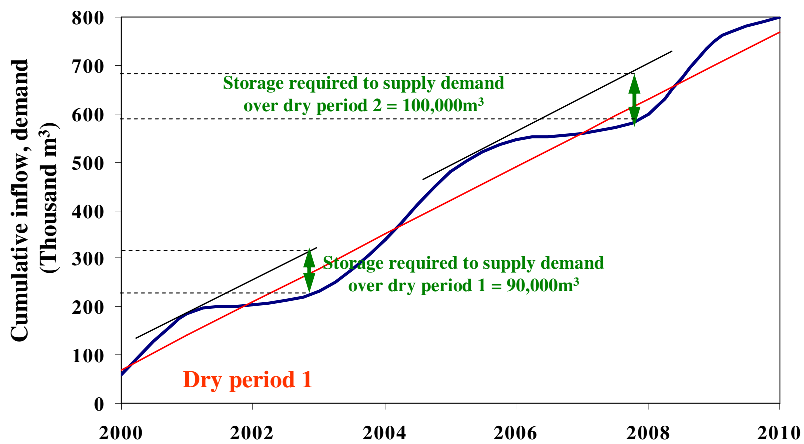
Step5: Find the storage required to supply the demand over the dry period.



Surface water storage

Soln:

Step6: Find the critical (maximum) storage required to supply the demand over the critical dry period. Storage = 100,000m^3.



Surface water storage

Storage capacity determination:

The sequent peak method is used to estimate the active storage capacity of reservoirs when the demand on water varies with time. In this method, the cumulative inflow determines the total supply, while the cumulative variable demand represents the total withdrawn. Our target is to maintain storage for the incoming flows during wet periods to overcome the largest deficit between the demand and the little inflow during the dry periods.

The following example will show detailed solution.

Surface water storage

Ex:

Use the sequent peak method to estimate the active storage capacity of a reservoir that will be installed on a river with yearly inflows as shown in the table to overcome the yearly demand on water as shown.

Year	Inflow (m^3/yr)	Demand (m^3/yr)
2000	60000	50000
2001	126000	75000
2002	19000	81000
2003	28000	77000
2004	107000	86000
2005	140000	66000
2006	66000	92000
2007	14000	44000
2008	40000	53000
2009	149000	51000
2010	51000	93000

Surface water storage

Soln:

Step1: Calculate the cumulative storage = Σ (inflow – demand).

Year	Inflow m^3	Demand m^3	Yearly storage m^3	Cumulative storage m^3	
2000	60000	- 50000	10000	10000	
2001	126000	75000	51000	61000	Surplus storage
2002	19000	81000	-62000 +	-1000	
2003	28000	77000	-49000	-50000	Deficit storage
2004	107000	86000	21000	-29000	
2005	140000	66000	74000	45000	Surplus storage
2006	66000	92000	-26000	19000	
2007	14000	44000	-30000	-11000	
2008	40000	53000	-13000	-24000	Deficit storage
2009	149000	51000	98000	74000	
2010	51000	93000	-42000	32000	

Surface water storage

Soln:

Step2: Determine the reservoir storage capacity from the analysis of the cumulative storage. The reservoir storage capacity is the difference between the surplus storage and deficit storage.

For dry period 1, the reservoir active storage =

= 61000 – (-50000) = 111000 m^3.

For dry period 2, the reservoir active storage =

= 45000 – (-24000) = 69000 m^3.

The critical storage is 111000m^3 which the reservoir active storage.

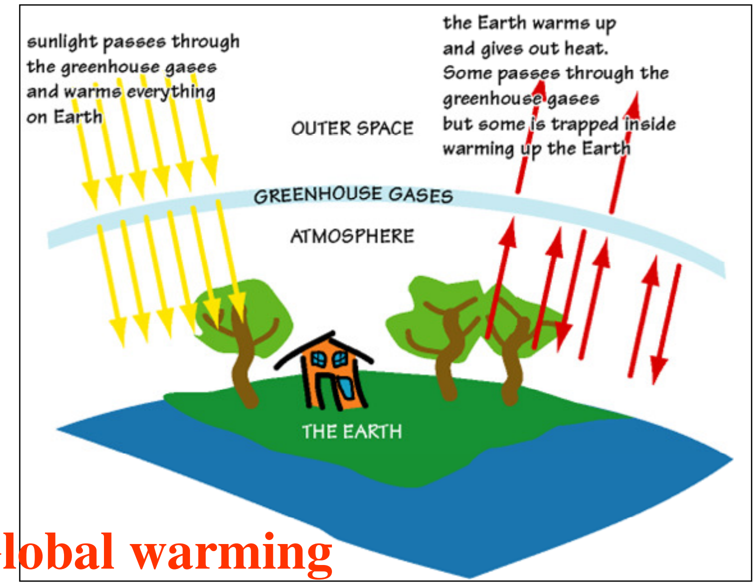
Surface water storage

Water losses from surface reservoirs:

Besides to sedimentation problem, water in surface reservoirs is exposed to losses including evaporation and leakage. The following measures can be adopted to reduce water losses:

- Constructing deep reservoirs to reduce evaporation,
- Planting tall trees around the reservoir to reduce the wind speed and hence reducing the potential evaporation,
- Covering the reservoir with plastic sheets (for small reservoirs).
- Removing weeds and un useful water plants.

Globe issue related to hydrology



Global warming

HYDROLOGY EXAM SHEET

Change in storage: ΔS = Vin - Vout

Watershed slope: S = ΔE/H

Drainage density: $D = \frac{\sum_{i=1}^{N} L_i}{A}$

Bifurcation ratio: $\frac{N_i}{N_{i+1}} = R_n$

Law of stream number: $N_i = R_n^{K-i}$

Law of stream length: $L_i = L_1 R_L^{i-1}$

The expected value (average): $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

Variance: $V = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2$

Standard deviation S = $\sqrt{V}$

Weibull plotting position: $P(X \le x) = \frac{m}{n+1}$

Exceedance probability $P(X > x) = 1 - P(X \le x)$

Return period: $T = \frac{1}{P(X > x)}$

Gumbel distribution (extreme value distribution): $P(X \le x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{x-u}{\alpha}\right]\right)\right]$

Distribution parameters $\alpha = \frac{\sqrt{6}\,S}{\pi}$ and $u = \bar{x} - 0.5772\,\alpha$

Extreme rainfall depth at duration d and return period T: $x_{d,T} = \bar{x}_d + K_T\,S_d$

Frequency factor $K_T = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \mathbf{ln}\left(\mathbf{ln}\left[\frac{T}{T-1}\right]\right)\right]$

Rainfall intensity $i(mm/hr) = \frac{x_{d,T}}{d}$

Rational method of peak flow (m^3/s): $Q = 0.278\,C\,i\,A$ (i in mm/hr) (A in km^2)

Time of concentration (minutes): $t_c = \frac{0.828\left(L \times n\right)^{0.467}}{S^{0.235}}$ (L in m) (n surface roughness)

Un-gauged site precipitation (point estimation): $P_{un-gauged} = \frac{\sum P \times W}{\sum W}$ $W = 1/D^2$

Areal precipitation: $\bar{P} = \frac{\sum P \times A}{\sum A}$

Evaporation rate: $E_r = \frac{R_n}{l_v \rho} \times k_s \times k_c$ R_n: Solar radiation, ρ = 1000 kg/m^3.

l_v (KJ/kg) = 2500 – 2.36 T

Infiltration rate: $f = f_c + (f_0 - f_c)e^{-kt}$ f_0: initial infiltration, f_c: equilibrium infiltration

Depression storage: $D_s = S_c\left(1 - e^{-P_n/S_c}\right)$ S_c: Storage capacity, P_n= total rain – E_r – f – interception.

Maximum retention storage: $S = \frac{1000}{CN} - 10$ Excess rain (inches) $P_e = \frac{(P - 0.2S)^2}{(P + 0.8S)}$

For AMC(I) dry soil: $CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)}$ For AMC(III) wet soil: $CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)}$

UH convolution equation: $Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1}$ or $Q_n = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + \dots + P_n U_1$

M: total # of rainfall pulses, P_m: excess rainfall depth (cm) at pulse m, U: unit hydrograph value.

$n = N - M + 1$, and N: total hydrograph time steps.

S-hydrograph from given X-hr UH: $S(t) = \Delta t_x \left[U_x(t) + U_x(t - \Delta t_x) + U_x(t - 2\Delta t_x) + U_x(t - 3\Delta t_x) \dots\right]$

Y-hr UH: $U_y(t) = \frac{1}{\Delta t_y}\left[S(t) - S(t - \Delta t_y)\right]$

Basin lag time (hrs) $T_L = C_t (L \times L_c)^{0.3}$ L & L_c in (km)

Duration of excess rainfall (hr) $D = \frac{T_L}{5.5}$ Adjusted basin lag time (hrs) $T_L' = T_L + 0.25(D' - D)$

For large basins, UH base time (days) $T_b = 3 + \frac{T_L'}{8}$ For small basins, UH base time (hrs) $T_b = 4T_L$.

Peak flow $Q_p = \frac{2.78 C_p A}{T_L'}$ Time to peak $T_p = \frac{D'}{2} + T_L'$

$W50 = 5.87(Q_p / A)^{-1.08}$ $W75 = \frac{W50}{1.75}$

Storage volume of existed reservoir $\Delta V_1 = \frac{h}{2}\left(A_1 + A_2\right)$

Darcy equation $V = -k\frac{\partial h}{\partial r} = -k\, s$

Steady flow from the confined aquifer: $Q = \frac{2\pi\, k\, D\left(h_2 - h_1\right)}{\ln\left(r_2 / r_1\right)}$

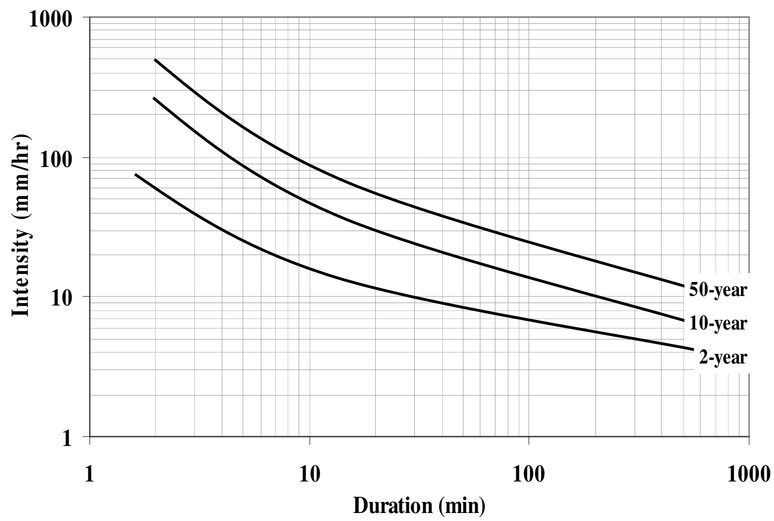
Steady flow from the unconfined aquifer: $Q = \frac{2\pi\, k\left(h_2^2 - h_1^2\right)}{\ln\left(r_2 / r_1\right)}$

Hydraulic conductivity $k_H = \frac{k_1 D_1 + k_2 D_2 + \ldots\ldots + k_n D_n}{D_1 + D_2 + \ldots\ldots + D_n}$

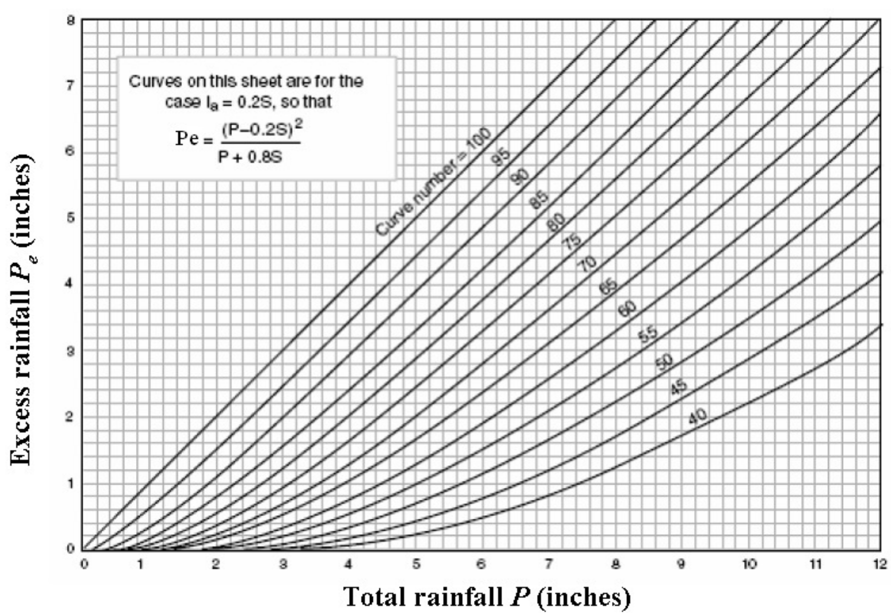
$$k_V = \frac{d_1 + d_2 + \ldots\ldots + d_n}{\frac{d_1}{k_1} + \frac{d_2}{k_2} + \ldots\ldots + \frac{d_n}{k_n}}$$

Drop in water table (non-equilibrium analysis) $s_d = \frac{Q}{4\pi T}\ln\left(\frac{2.25\,T\,t}{r^2\,S}\right)$

IDF curve



CN



Contemporary issues

Contemporary issues related to hydrology:

They are hot issues that may create dramatic change to part or all of the hydrological input and output variables. Hydrological input variables like: the amount of the rainfall and its time and spatial distribution, wind speed and direction, soil size and surface texture of the watershed.

Hydrological outputs variables like evaporation and infiltration amount, the peak flow value and time to peak, extreme floods and extreme drought incidents, the final water volume that can be harvested and water storage, water pollution.

Contemporary issues

Contemporary issues related to hydrology:

Among many contemporary issues related to hydrology, the following list of issues will be defined and discussed in terms of the consequences of such problems.

- Climate change and its effect,
- Urbanization and its effect,
- The stressed water resources in Jordan.

Contemporary issues

Climate change:

Recent comparative studies have noticed several changes in climatic variables like the temperature, the relative humidity, the amount of the rainfall, the temporal and spatial distribution of the rainfall over the whole earth or a specific region.

Causes of the climate change??? There are two opinions:

- Due to the effect of the greenhouse gases (feasible opinion = proved by studies results).
- Due to natural behavior of the earth climate.

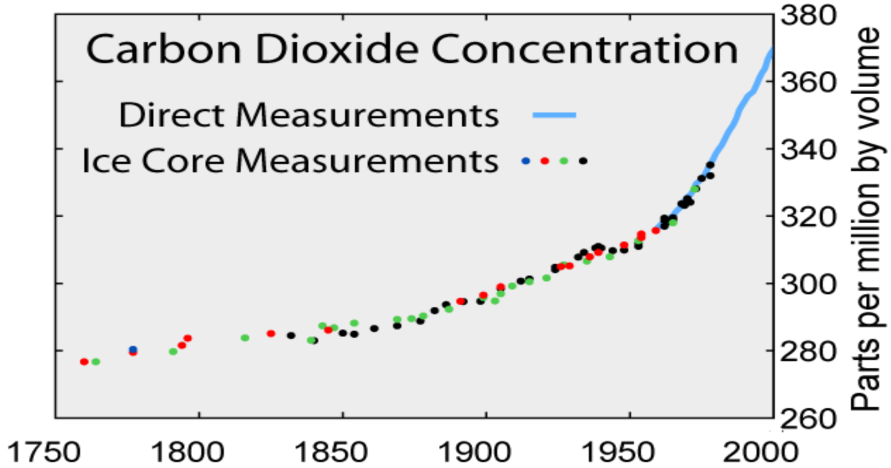
Contemporary issues

Climate change due to greenhouse gases:

Greenhouse gases (like CO_x and NO_x) are gases exist in the earth atmosphere with ability to absorb and emit radiant energy within the thermal infrared range causing the greenhouse phenomenon. In recent decades, the concentrations of the greenhouse gases have been increased in the atmosphere several times higher than normal values. For example, the concentration of the CO_2, the major gas that causes the greenhouse, has been increased from 280ppm in 1750 (beginning of the industrial era) to about 406ppm in 2017 (refer to next figure).

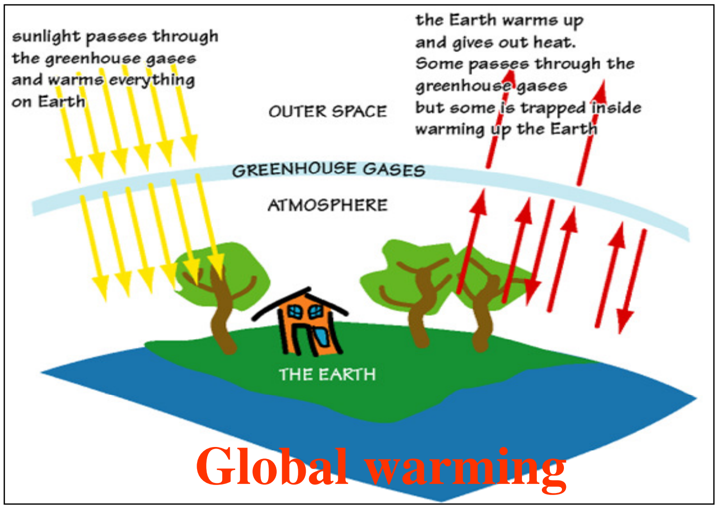
Contemporary issues

Climate change: CO_2 concentrations



Contemporary issues

Climate change: the greenhouse mechanism.



Contemporary issues

Climate change due to greenhouse gases:

The main source of the greenhouse gases (CO_x and NOx) especially the CO_2 gas are:

- The increasing industrial activities: especially those rely on the fossil fuel (Oil) as an energy source.
- Deforestation: trees absorb CO_2 for cells synthesis, i.e. trees decrease the concentration of the CO_2 gas.
- Agricultural activities: the use of the Nitrogen components increases the NO_x gases concentrations.
- Natural activities (like volcano activities and forest fire). Such activities increase the CO_2 concentration in the earth atmosphere.

Contemporary issues

Climate change due to greenhouse gases:

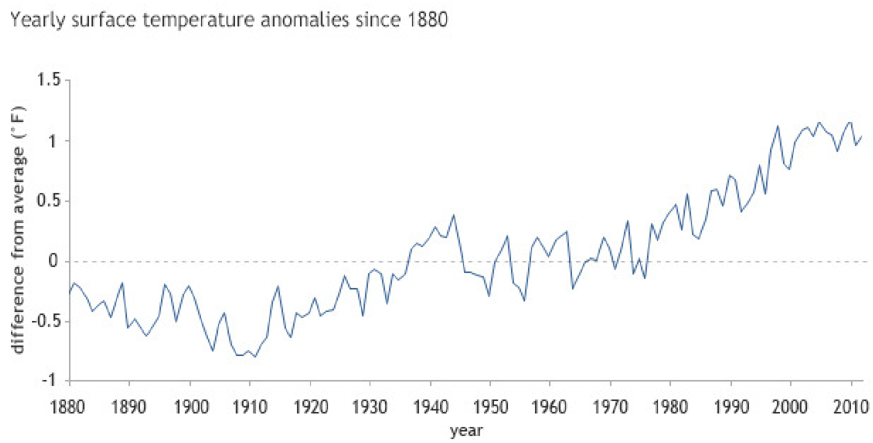
The consequences of the greenhouse effect:

- Increasing the earth temperature (Global warming), that rising the sea water level, bringing extreme floods and droughts.
- Affecting the ecosystems and biodiversity,
- Increasing the oceans acidity,
- Depleting the ozone layer.

Contemporary issues

Climate change due to greenhouse gases:

The increase in the earth temperature.



Contemporary issues

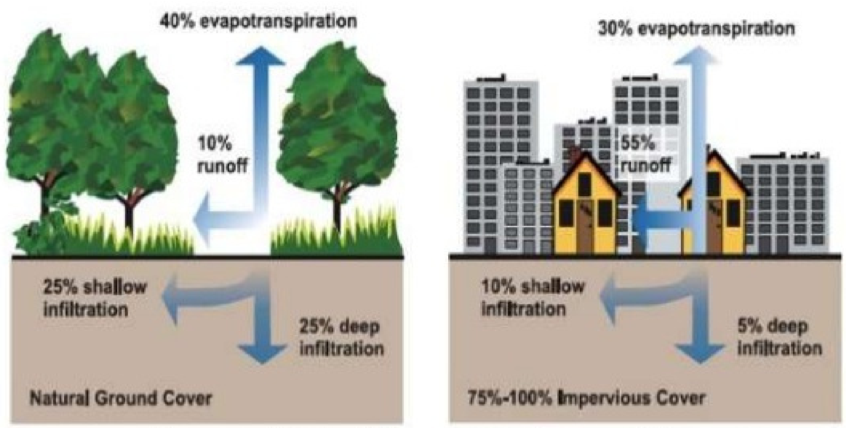
Effect of urbanization:

Urbanization is the modification the humans have made on the earth nature. For example, some dramatic changes were happened to the land surface due to human activities (infrastructure systems) like buildings, paved areas (streets and parking lots). As a result, the land surface becomes more smooth and the soil porosity has decreased. Since the land surface becomes smooth and the infiltration rate has decreased, rapid and high peak floods occur.

Urbanization also has affected the wind direction and the amount of the evapo-transpiration due to the removal of trees.

Contemporary issues

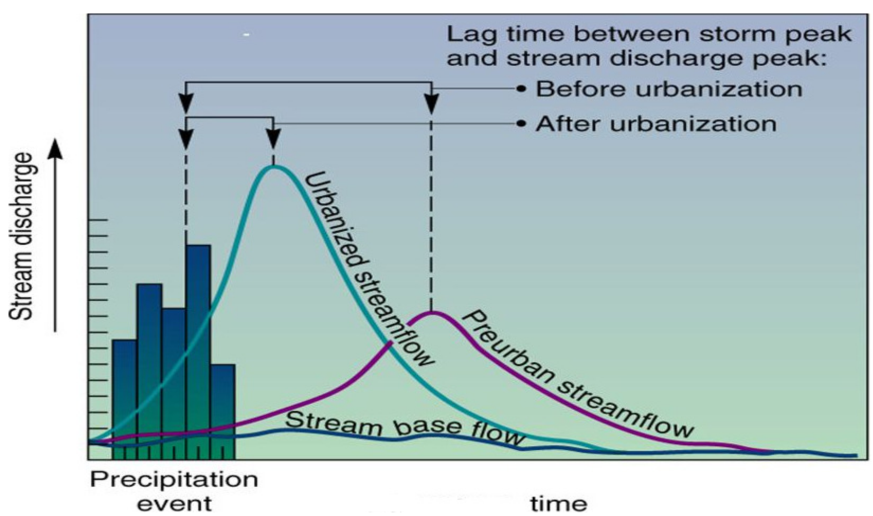
Effect of urbanization:



Source: thebritishgeographer.weebly.com

Contemporary issues

Effect of urbanization:



The stressed water resources in Jordan

In Jordan, the water resources are limited, and the demand on water for domestic, agriculture and industrial activities has exceeded the available water from natural resources. Therefore, our national water resources are under persistent stress. The following table shows past facts and future scenarios about the demand versus the supply in Jordan.

Year	Demand (Mm^3)	Available water (Mm^3)	Deficit (Mm^3)
2010	1383	1054	329
2020	1602	1152	450
2040	2236	1549	687

The stressed water resources in Jordan

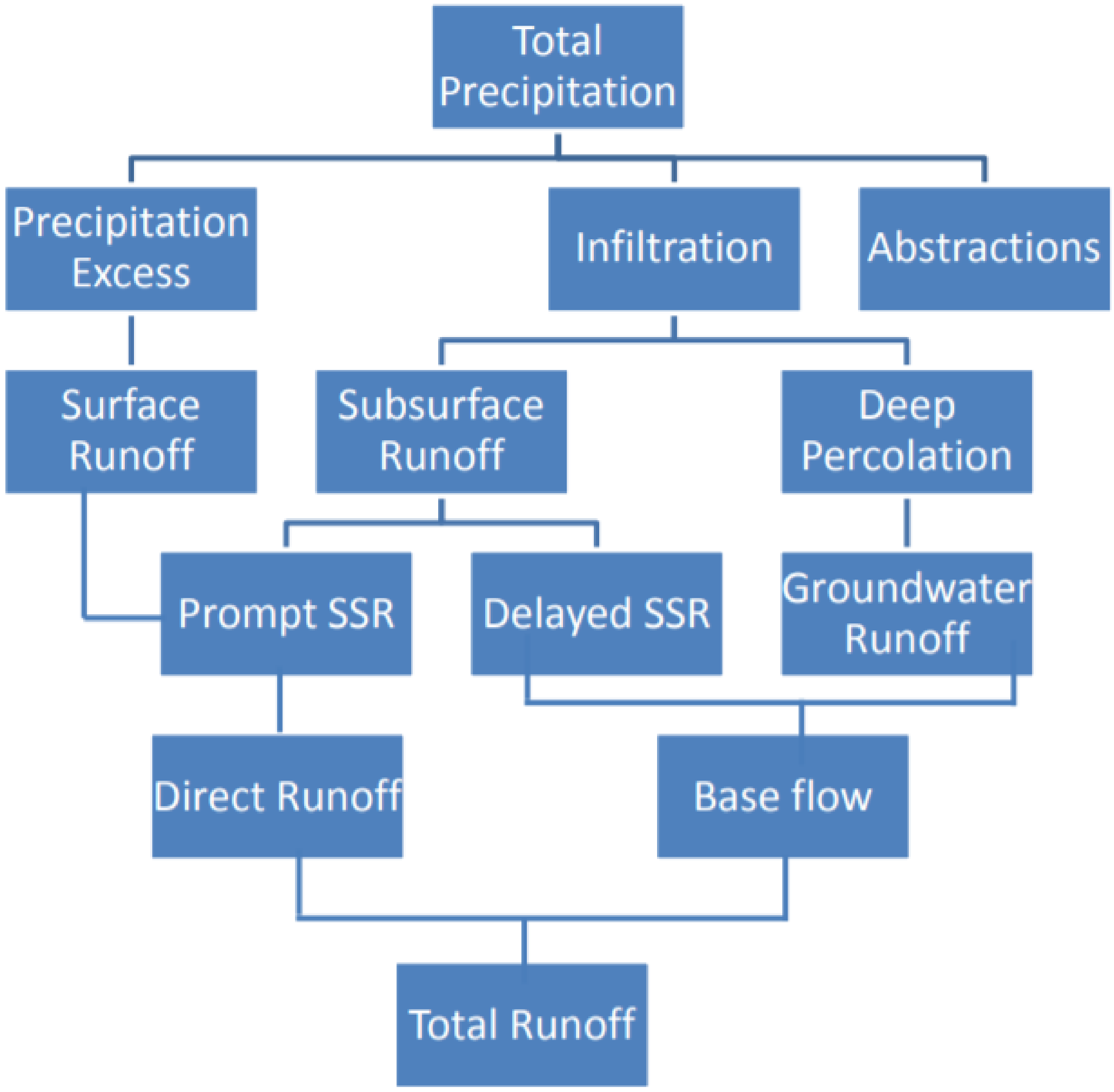
Sustainable solutions to water crisis in Jordan:

- Adapting water policy that encourages the efficient water use (water savings),
- Increasing the rainwater harvesting,
- Finding new non-traditional water sources like desalting sea and brackish water.
- Enhancing existing non-traditional water sources, for example increasing the treated wastewater amounts and water reuse.

Think about other solution not being mentioned here.

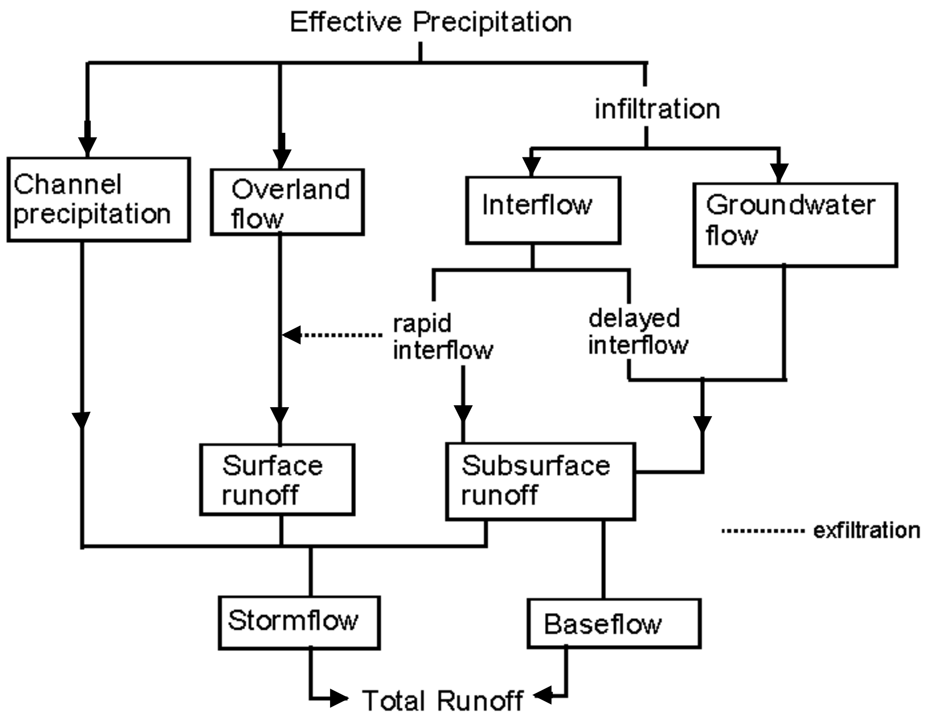
Hydrologic Parameters
Runoff

- Runoff is the portion of rainfall which flows through the rivers, streams etc.



Type of runoff

- Surface runoff – Portion of rainfall (after all losses such as interception, infiltration, depression storage etc. are met) that enters streams immediately after occurring rainfall - After laps of few time, overland flow joins streams – Sometime termed prompt runoff (as very quickly enters streams)
- Subsurface runoff – Amount of rainfall first enter into soil and then flows laterally towards stream without joining water table - Also take little time to reach stream



Runoff Computation - Rational Method

$$Q = CiA$$

Where:

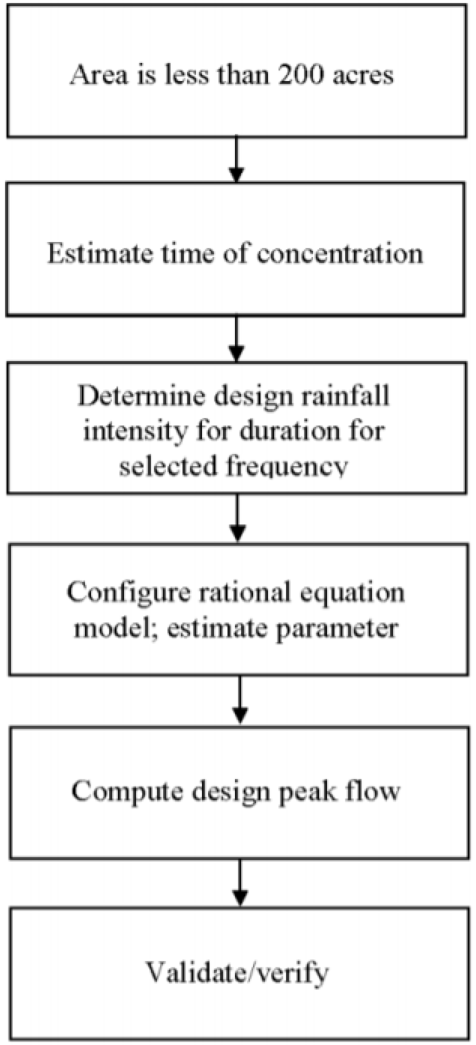
Q = Maximum Rate of Runoff (cfs)
C = Runoff Coefficient
i = Average Rainfall Intensity (in/hr)
A = Drainage Area (in acres)

An urban area consisting of sub-areas with different surface characteristics

$$Q = i\sum_{j=1}^{m} C_j A_j$$ **Composite rational equation**

j = number of sub-catchments drained by a sewer

Rational Method



Assumptions and Limitations:

- Watershed area < 200 acres
- The method is applicable if time of concentration (t_c) for the drainage area is less than the duration of peak rainfall intensity.
- The time of concentration (t_c) is the time required for water to travel from the hydraulically most remote point of the basin to the point of interest.

Rational Method

Assumptions and Limitations:

- The calculated runoff is directly proportional to the rainfall intensity.
- Rainfall intensity is uniform throughout the duration of the storm.
- Rainfall is distributed uniformly over the drainage area.
- The minimum duration to be used for computation of rainfall intensity is 10 minutes.

Runoff Coefficient (C)

Definition: Dimensionless ratio intended to indicate the amount of runoff generated by a watershed given a average intensity of precipitation for a storm.

$$C = \frac{R}{P}$$

Where: R = Total depth of runoff P = Total depth of precipitation

Runoff Coefficient (C)

Table 1 Runoff Coefficients for the Rational Method

	FLAT	ROLLING	HILLY
Pavement & Roofs	**0.90**	**0.90**	**0.90**
Earth Shoulders	0.50	0.50	0.50
Drives & Walks	0.75	0.80	**0.85**
Gravel Pavement	**0.85**	**0.85**	**0.85**
City Business Areas	0.80	**0.85**	**0.85**
Apartment Dwelling Areas	0.50	0.60	0.70
Light Residential: 1 to 3 units/acre	0.35	0.40	0.45
Normal Residential: 3 to 6 units/acre	0.50	0.55	0.60
Dense Residential: 6 to 15 units/acre	0.70	0.75	0.80
Lawns	0.17	0.22	0.35
Grass Shoulders	0.25	0.25	0.25
Side Slopes, Earth	0.60	0.60	0.60
Side Slopes, Turf	0.30	0.30	0.30
Median Areas, Turf	0.25	0.30	0.30
Cultivated Land, Clay & Loam	0.50	0.55	0.60
Cultivated Land, Sand & Gravel	0.25	0.30	0.35
Industrial Areas, Light	0.50	0.70	0.80
Industrial Areas, Heavy	0.60	0.80	**0.90**
Parks & Cemeteries	0.10	0.15	0.25
Playgrounds	0.20	0.25	0.30
Woodland & Forests	0.10	0.15	0.20
Meadows & Pasture Land	0.25	0.30	0.35
Unimproved Areas	0.10	0.20	0.30

Rainfall intensity (i)

- The determination of rainfall intensity (i) for use in the Rational Formula involves consideration of three factors:

- Average frequency of occurrence.
- Intensity-duration characteristics for a selected rainfall frequency.
- The time of concentration (t_c).

Time of Concentration (t_c)

- Definition: The time required for a parcel of runoff to travel from the most hydraulically distant part of a watershed to the outlet.

- tc represents the time at which all areas of the watershed that will contribute runoff are just contributing runoff to the outlet.

Time of Concentration (t_c)

Morgali and Linsley Method (1965)

$$t_c = \frac{0.94(nL)^{0.6}}{i^{0.4}S^{0.3}}$$

t_c = time of concentration (min),
i = design rainfall intensity (in/hr),
n = Manning surface roughness (dimensionless),
L = length of flow (ft), and
S = slope of flow (dimensionless).

Table 3-2. Manning's Roughness Coefficient (n) for Overland Sheet Flow[8].

Surface Description	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipe	0.024
Cement rubble surface	0.024
Fallow (no residue)	0.05
Cultivated soils	
Residue cover ≤ 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short grass prairie	0.15
Dense grasses	0.24
Bermuda grass	0.41
Woods*	
Light underbrush	0.40
Dense underbrush	0.80

*When selecting n, consider cover to a height of about 30 mm. This is only part of the plant cover that will obstruct sheet flow.

Time of Concentration (t_c)

Kirpich Method (1940)

$$t_c = 0.0078(L^3/h)^{0.385}$$

$t_c =$ time of concentration (min),

$L =$ length of main channel (ft), and

$h =$ relief along main channel (ft).

Assumptions and Limitations:

- For small drainage basins dominated by channel flow.

Time of Concentration (t_c)

Kerby-Hatheway Method (1959)

$$t_c = \left[\frac{0.67NL}{\sqrt{S}}\right]^{0.467}$$

t_c = time of concentration (min),
N = Kerby roughness parameter (dimensionl
S = overland flow slope (dimensionless).

Assumptions and Limitations:

- Primarily used for overland flow.

Table 3: Kerby's roughness parameter.

Description	N
Pavement	0.02
Smooth, bare packed soil	0.10
Poor grass, cultivated row crops or moderately rough bare surfaces	0.20
Pasture, average grass	0.40
Deciduous forest	0.60
Dense grass, coniferous forest, or deciduous forest with deep litter	0.80

Time of Concentration (t_c)

Time of Concentration (t_c)

Numerous Flow Segments

$$t_c = t_{t1} + t_{t2} + \ldots + t_{tn}$$

Where:

t_c = Time of Concentration
t_{t1} = Travel time of Segment 1
n = Number of segments

Example

Given T_d =10 min, C = 0.6, ground elevations at the pipe ends (498.43 and 495.55 ft), length = 450 ft, Manning n = 0.015, $i = 120T^{0.175}/(T_d + 27)$, compute flow, pipe diameter and flow time in the pipe. Knowing that area of drainage is 4 acre.

$$i = \frac{120(5)^{0.175}}{(10+27)} = 4.30 \;\; in/hr$$

$$Q = CiA = 0.6 \times 4.30 \times 4 = 10.3 \;\; cfs$$

$$D = \left(\frac{2.16Qn}{\sqrt{S_0}}\right)^{3/8} = \left(\frac{2.16 \times 10.3 \times 0.015}{\sqrt{0.0064}}\right)^{3/8} = 1.71 \;\; ft = 1.75 \;\; ft$$

$$Flow\ time = length\ of\ \ pipe\ /\ velocity$$

$$= \frac{450}{Q} \times A_{pipe} = \frac{450}{10.3} \times \frac{\pi \times 1.75^2}{4}$$

$$= 105\ sec = 1.75\ min$$

Manning's equation

$$Q = \frac{1.49}{n} A R^{2/3} S_f^{1/2} \qquad D = \left(\frac{2.16 Q n}{\sqrt{S_0}} \right)^{3/8}$$

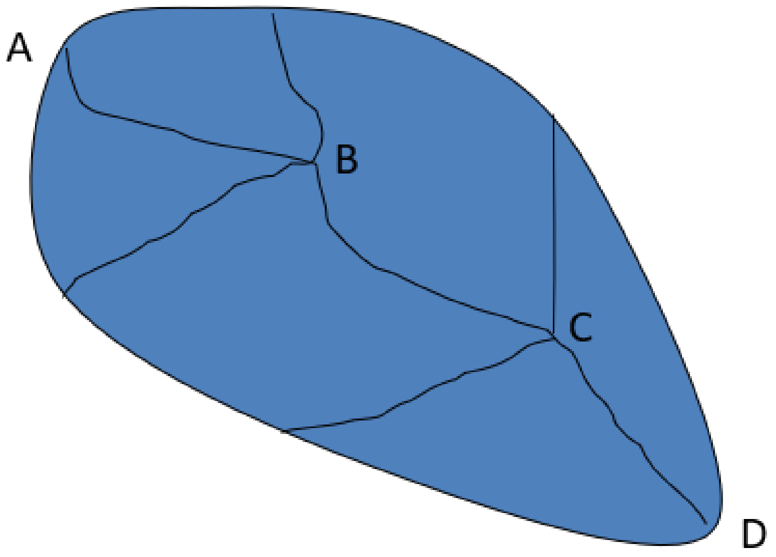
Valid for Q in cfs and D in feet. For SI units (Q in m^3/s and D in m), replace 2.16 with 3.21.

Darcy-Weisbach equation

$$Q = A \left(\frac{8g}{f} R S_f \right)^{1/2} \qquad D = \left(\frac{0.811 f Q^2}{g S_o} \right)^{1/5}$$

Equation is valid for both SI and English system as long as the units are consistent

Example



Compute t_c and peak flow at D for I = 3.2 in/hr

Reach	Description of flow	C	Slope (%)	Length (ft)	Area (acre)
A-B	Natural channel	0.41	4.5	300	8
B-C	Natural channel	0.85	3	540	20
C-D	Storm drain (n = 0.015, D = 3 ft)	0.81	1.2	500	10

Solution

Compute t_c for AB and BC using Kirpich formula

$$t_c(AB) = 0.0078 L^{0.77} S^{-0.385} = 0.0078 \times 300^{0.77} \times (0.045)^{-0.385} = 2.8 \ \text{min}$$

$$t_c(BC) = 0.0078 L^{0.77} S^{-0.385} = 0.0078 \times 540^{0.77} \times (0.03)^{-0.385} = 3.8 \ \text{min}$$

For CD, compute velocity by Manning's equation and t_c = length/velocity

$$V_{CD} = \frac{1.49}{n} R^{2/3} S^{1/2} = \frac{1.49}{0.015} \times (3)^{2/3} \times (0.012)^{1/2} = 9 \ ft/s$$

$$t_c(CD) = 500/9 = 55 \ s = 1 \ \text{min}$$

$$t_c(AD) = 2.8 + 3.8 + 1 = 7.6 \ \text{min}$$

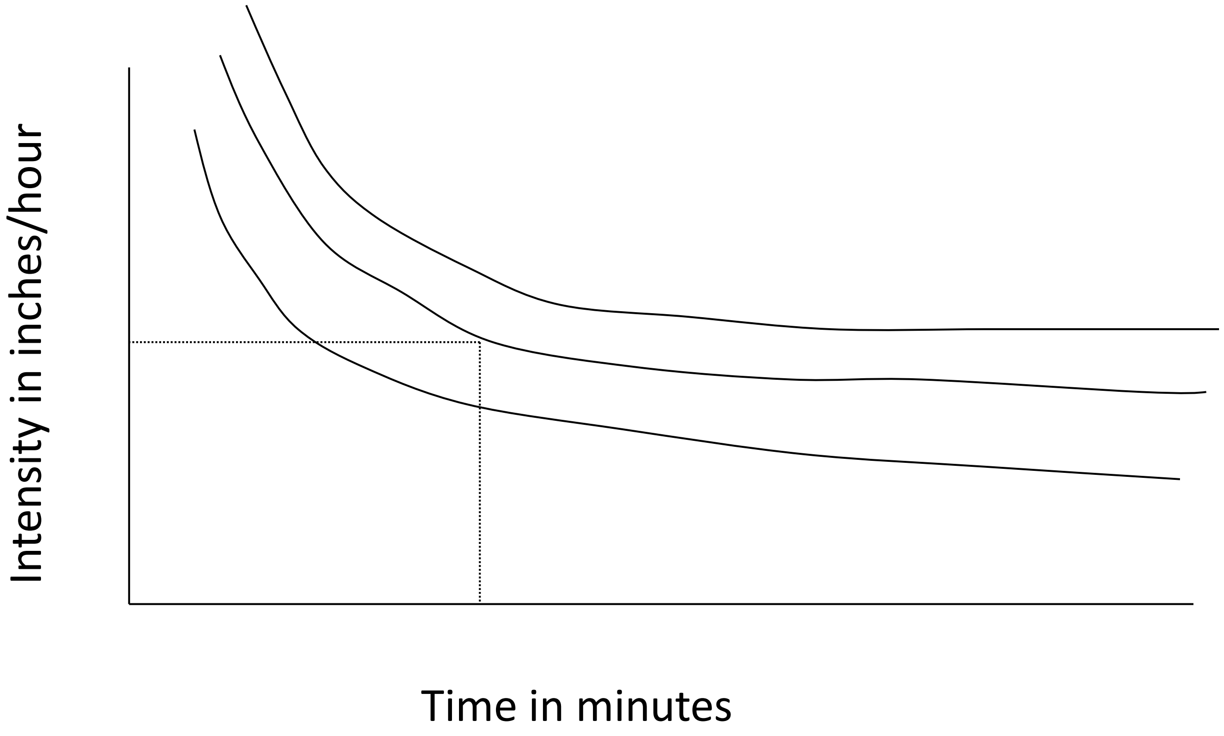
$$Q_p = i \sum c_j A_j = 3.2 \times (0.41 \times 8 + 0.85 \times 20 + 0.81 \times 10) = 90.8 \ cfs$$

Probabilistic
Rainfall Characteristics

- Intensity
- Duration
- Frequency
- Amount
- Time Distribution
- Spatial Variability

Rainfall Patterns

Typically characterized by *intensity-duration-frequency (IDF) curves*



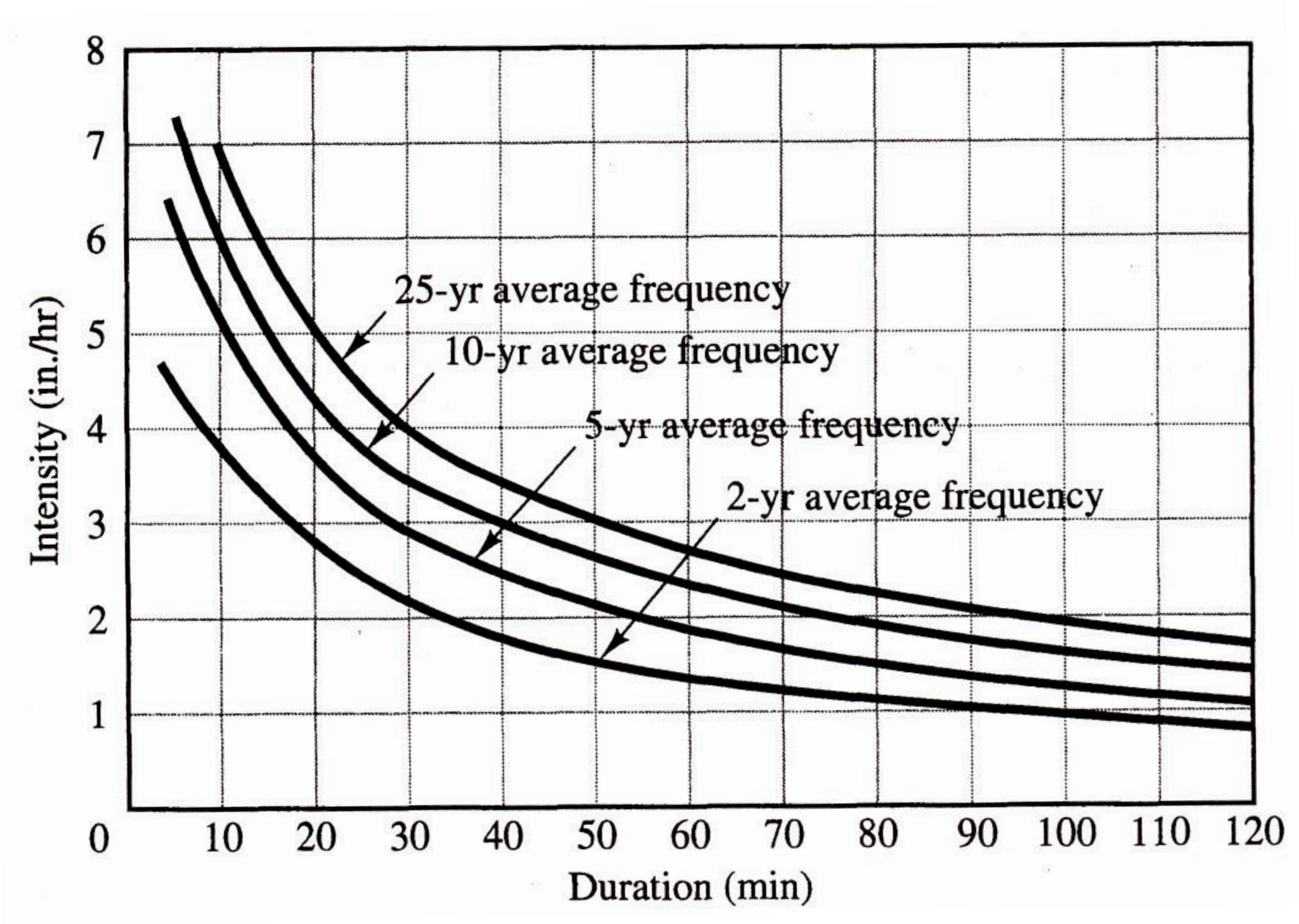
Duration

- The duration of the storm is directly related to the volume of surface runoff.
- High intensities are generally associated with short duration storms. Large water volumes are generally associated with long duration storms.

Frequency

- The frequency of occurrence of a storm of given magnitude and duration is important to establish a measure of risk.
- For a given storm duration, the probability that an event of certain magnitude has of being equaled or exceeded in any one year is termed the probability of exceedance.
- In general, for the same return period, short storms are more intense than long storms. Similarly, for a given intensity, longer storms are associated with greater return periods.

IDF Curves



IDF curves show frequency of storms of *at least* the given intensity over the given duration.

Hydrology
CE 454

Statistical methods in hydrology/ Flood frequency

Flood Frequency

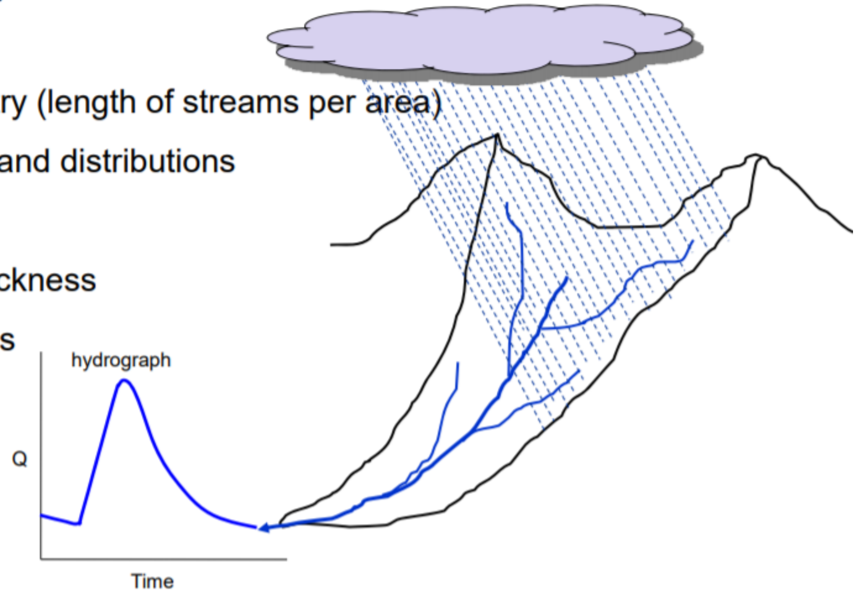
The frequency is the number of time that a given magnitude flood may occur in a given period.

Turkey2009

Japan 2017

FLOODS are usually caused by heavy rains and/or rapid snow melt—their severity is controlled by the watershed characteristics.

1. Basin size (area)
2. Topography
3. Drainage dentistry (length of streams per area)
4. Vegetation type and distributions
5. Geology
6. Soil type and thickness
7. Runoff processes



Flooding effects about 75 million people per year

An aerial view of the flooded I-5 overpass looking south Flooding in Chehalis (December 04, 2007)

Floods are the #1 weather-related killer in the U.S.

Cowlitz River near Packwood, Washington

Cont. Flood frequency

Flood frequency is the concept of the probable frequency of occurrence of a given flood. For the design of engineering works, for example, it is not sufficient to say that the maximum observed flood was, say, 900 m^3/s; it is also necessary to say what is the frequency of occurrence of this flood.

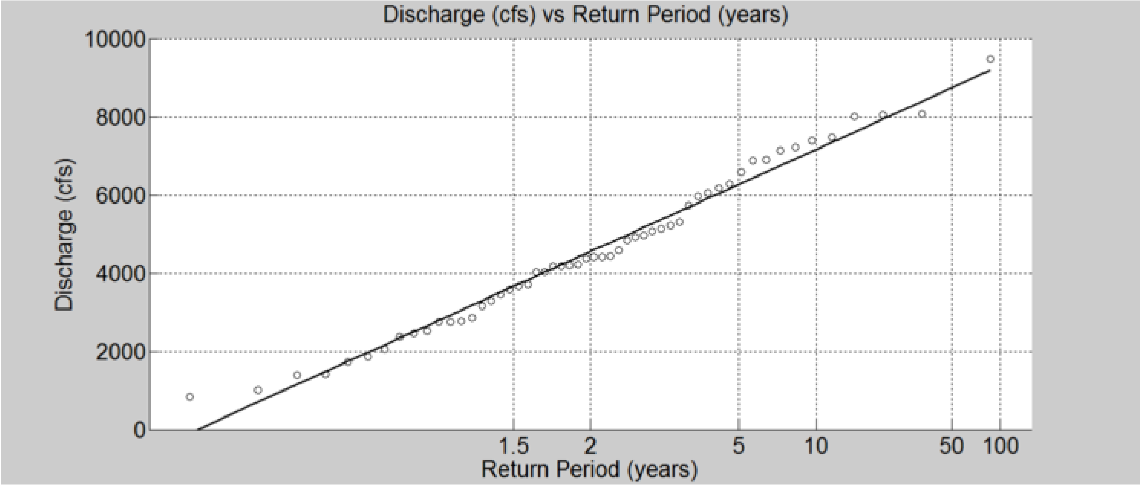
There are several ways of describing flood frequency, all using statistical probability.

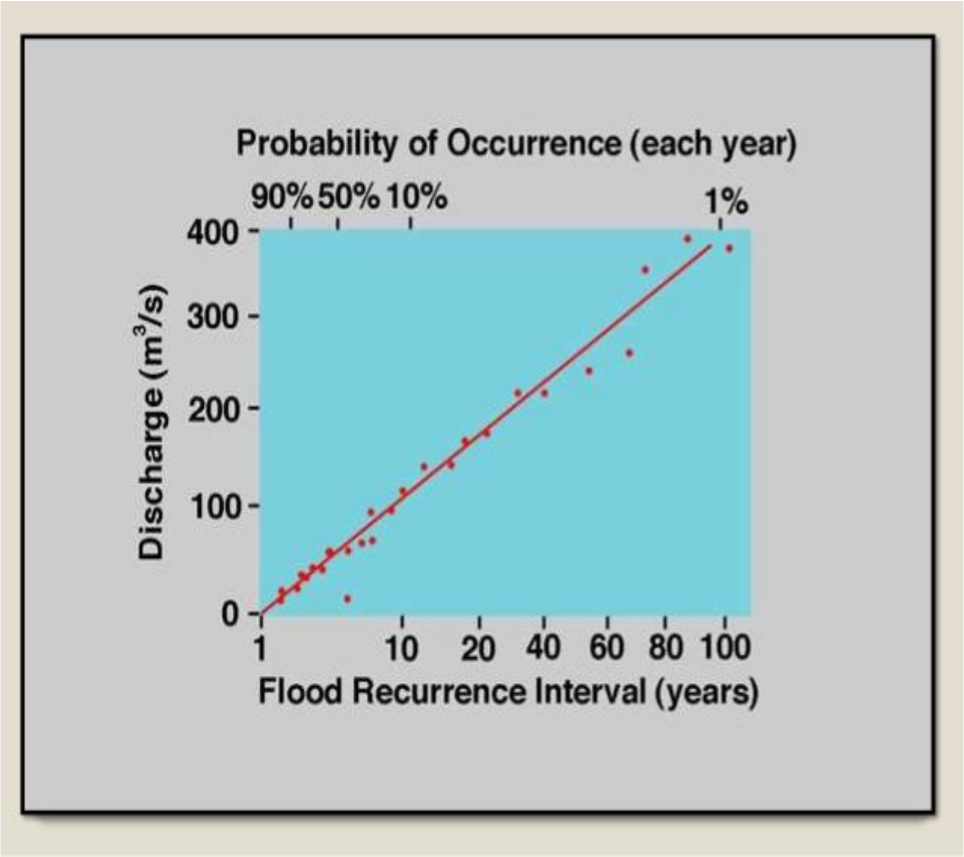
1. Assigning *return periods* to particular floods was traditionally used, but is an unhelpful term when trying to explain its meaning to the public and others. An example of a return period is when a flood has a 1 % probability of occurring in a given year (i.e. 1 chance in 100) and is thus described as a 100-year flood event. This term suggests the common but mistaken notion that there should be an interval of 100 years between such events. In fact, the probability of having two 100-year floods within 10 years is almost 10 %.
2. The *annual exceedence probability* (AEP) is also used. This is simply the probability that a particular flood size will occur in any given year. As for the example above, the 100-year flood will have an AEP of 1 % (or 1 chance in 100). Explaining the probability to the public in this way is usually better.
3. The *probable maximum flood* (PMF) concept is sometimes used for engineering applications. Again, this is similar to the above two methods, and often uses the 100-year / 1 % probability, as many designs are based on this. However PMF also implies a lower probability than 1 %, and values as low as 0.1 % will be used for some applications. Trying to derive a PMF is usually very risky unless there is a very long record.

- For the evaluation of **flood frequency** can be classified into **two approaches:**
  - (1) **Statistical approach** estimates flood quantiles by applying **probability** models.
  - (2) The design storm method uses the **rainfall-runoff model.**

- In **statistical** Method:
  1) Probability plotting method
  2) Weibull formula
  3) Hazen method
  4) California method
  5) Gumbel's method

- From this all method **Weibull** formula is most commonly used.





A “100-year flood” is a flood that has a 1% chance of occurring in any given year

Nooksack River in Whatcom County, Jan 9, 2009

How to determine the discharge of a “100-year flood”

Frequency analysis

- Probability of exceedance (P): the probability in which a certain event (rainfall) is equaled or exceeded.
- Return period (recurrence interval) , Tr: the average interval in years within which a given event will be equaled or exceeded

Exceedance obability(P), %	Return Period (Tr) Years	Rainfall equalled or exceeded
100	1	Every Year
80	1.25	Once in 1.25 years (4 times in 5 years)
75	1.33	Once in 1.33 years (3 times in 4 years)
67	1.5	Once in 1.5 years (2 times in 3 years)
1	100	Once in 100 years

Frequency analysis steps

- Step 1 : Obtain annual rainfall totals for the cropping season from the area of concern.

- Step 2 : Arrange the rainfall data in the descending order of magnitude.

- Step 3 : Give ranks (m) to each ordered data. Rank of 1 for the largest value and n for the smallest value, where n is the number of data points.

- Step 4 : Determine the recurrence interval Tr of each rainfall value using formula: $Tr = (N+1) / m$, or any other position formulae.

Frequency analysis steps

- Step 5 : Compute the probability of exceedance P,

  $$P = 1 / T_r = (m) / (n + 1)$$

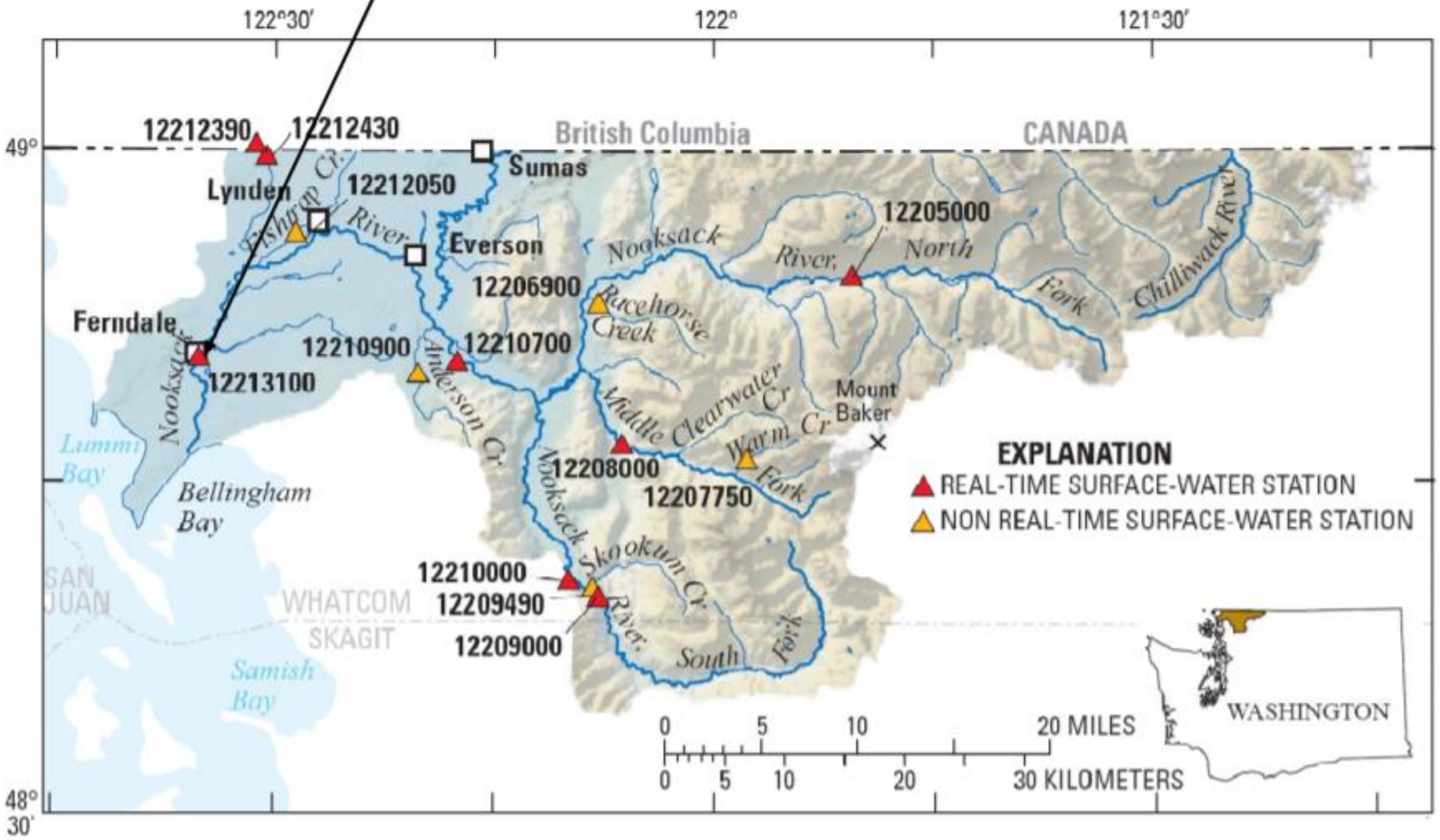
- Step 6 : Plot the value of P or Tr against the corresponding magnitude of rainfall data, on probability paper , & fit a line for the plotted data.

- Step 7 : To determine the design rainfall look the corresponding value of rainfall for the exceedance probability used.

Plotting position formulae

Name of formula	*Year in which introduced*	$T = \dfrac{1}{P(X \geq x)}$
California	1923	N/m
Hazen	1930	$2N/(2m - 1)$
Weibull	1939	$(N + 1)/m$
Chegodayev	1955	$(N + 0.4)/(m - 0.3)$
Blom	1958	$(N + 0.25)/(m - 0.375)$
Tukey	1962	$(3N + 1)/(3m - 1)$
Gringorten	1963	$(N + 0.12)/(m - 0.44)$
Cunnane	1989	$(N + 0.2)/(m - 0.4)$

1. Collect the historical peak flows for a river (e.g., Nooksack at Ferndale).



Example

1. Collect the historical peak flows for a river (e.g., Nooksack at Ferndale).

Year	cfs	Year	cfs	Year	cfs	Year	cfs
10/26/1945	41600	12/14/1966	21400	4/27/1985	16300	1/26/2003	20100
11/27/1949	27500	12/26/1967	23900	2/25/1986	29900	10/21/2003	39900
2/10/1951	55000	1/5/1969	28100	11/24/1986	36000	11/25/2004	42300
1/31/1952	18300	11/5/1969	17300	4/6/1988	17700	1/10/2006	19500
2/1/1953	19300	1/31/1971	38100	10/16/1988	21000	11/7/2006	38100
10/31/1953	18500	3/6/1972	24800	11/11/1989	47800	12/4/2007	21100
11/19/1954	20700	12/26/1972	24800	11/10/1990	57000	1/8/2009	51700
11/4/1955	35000	1/17/1974	21800	1/24/1992	18100		
12/10/1956	23000	12/21/1974	20800	1/25/1993	19000		
1/17/1958	18300	12/3/1975	46700	3/2/1994	18500		
4/30/1959	30200	1/18/1977	20600	12/20/1994	21700		
11/23/1959	22000	12/3/1977	23900	11/30/1995	47200		
1/16/1961	30800	11/8/1978	18800	3/20/1997	38100		
1/8/1962	18800	12/15/1979	36400	10/30/1997	17600		
11/20/1962	26000	12/27/1980	29700	12/14/1998	24600		
11/27/1963	23300	2/15/1982	27200	12/16/1999	22200		
1/31/1965	20000	1/11/1983	34200	10/21/2000	14300		
12/4/1965	17500	1/5/1984	41500	2/23/2002	30300		

Note : This example is solved using Weibull formula

2. “Rank” the peak flow discharges from highest to lowest.

Rank	cfs
1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
15	36000
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900

1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
15	36000
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900
22	29700
23	28100
24	27500
25	27200
26	26000
27	24800
28	24800
29	24600
30	23900
31	23900
32	23300
33	23000
34	22200
35	22000
36	21800
37	21700
38	21400
39	21100
40	21000
41	20800
42	20700
43	20600
44	20100
45	20000
46	19500
47	19300
48	19000
49	18800
50	18800
51	18500
52	18500
53	18300
54	18300
55	18100
56	17700
57	17600
58	17500
59	17300
60	16300
61	14300

3. Estimate the **exceedance probability** using the ranked values and the Weibull position formula.

$$P = \frac{m}{n+1}$$

m = rank

n = total number of values

in this case “n = 61”

2. “Rank” the peak flow discharges from highest to lowest.

Rank	cfs
1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
$\boxed{15}$	$\boxed{36000}$
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900

1	57000
2	55000
3	51700
4	47800
5	47200
6	46700
7	42300
8	41600
9	41500
10	39900
11	38100
12	38100
13	38100
14	36400
15	36000
16	35000
17	34200
18	30800
19	30300
20	30200
21	29900
22	29700
23	28100
24	27500
25	27200
26	26000
27	24800
28	24800
29	24600
30	23900
31	23900
32	23300
33	23000
34	22200
35	22000
36	21800
37	21700
38	21400
39	21100
40	21000
41	20800
42	20700
43	20600
44	20100
45	20000
46	19500
47	19300
48	19000
49	18800
50	18800
51	18500
52	18500
53	18300
54	18300
55	18100
56	17700
57	17600
58	17500
59	17300
60	16300
61	14300

Example: for $m = 15$

$$P = \frac{m}{n + 1}$$

m = rank

n = total number of values

$$P = \frac{15}{61 + 1} = 0.24$$

The discharge for "m = 15" is 36,000 cfs. This means that in any given year there is a 0.24 probability or a 24% chance of a "peak flow" occurring that will equal or exceed a Q of 36,000 cfs.

4. The exceedance probability can be used to estimate the **return period** of a certain peak flow (i.e., how often can we expect a certain magnitude flood?)

$$\text{Return Period} = \frac{1}{P}$$

Example: for $m = 15$ where $P = 0.24$

$$\text{Return Period} = \frac{1}{0.24} = 4.13 \text{ years}$$

The means that one can expect a flood with a peak flow of about 36,000 cfs every 4.13 years.

A 100-year flood is a flood that has a return period of 100 years

OR a probability of 0.01 of occurring in any given year

OR a 1% chance of occurring in any given year

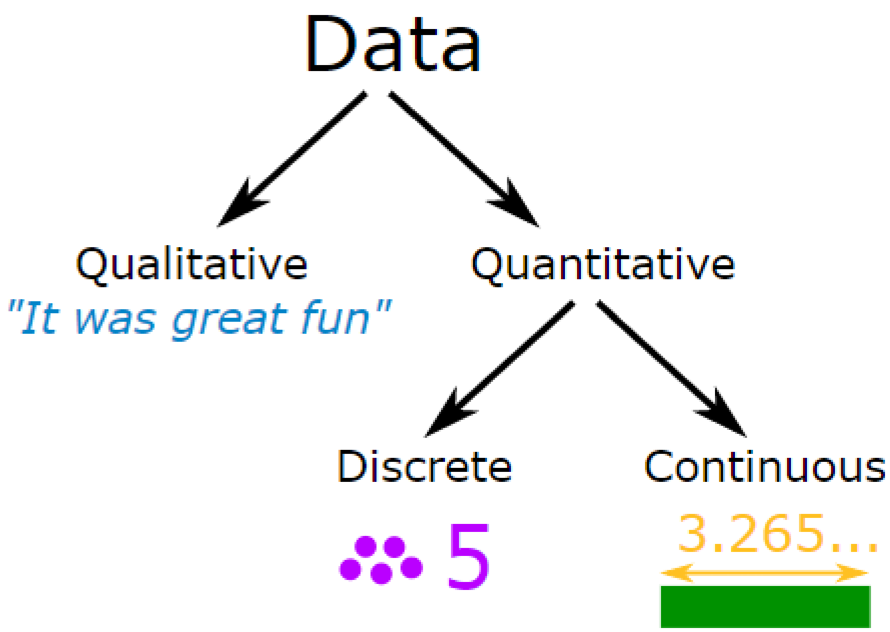
How Can We Have two "100-year floods" in less than two years?

- This question points out the importance of proper terminology. The term "100-year flood" is used in an attempt to simplify the definition of a flood that statistically has a 1-percent chance of occurring in any given year. Likewise, the term "100-year storm" is used to define a rainfall event that statistically has this same 1-percent chance of occurring. In other words, over the course of 1 million years, these events would be expected to occur 10,000 times. But, just because it rained 10 inches in one day last year doesn't mean it can't rain 10 inches in one day again this year.

Recurrence intervals and probabilities of occurrences

Recurrance interval, in years	Probability of occurrence in any given year	Percent chance of occurrence in any given year
100	1 in 100	1
50	1 in 50	2
25	1 in 25	4
10	1 in 10	10
5	1 in 5	20
2	1 in 2	50

Continuous and discrete Data

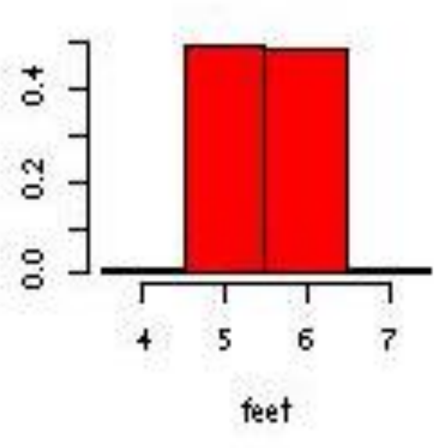


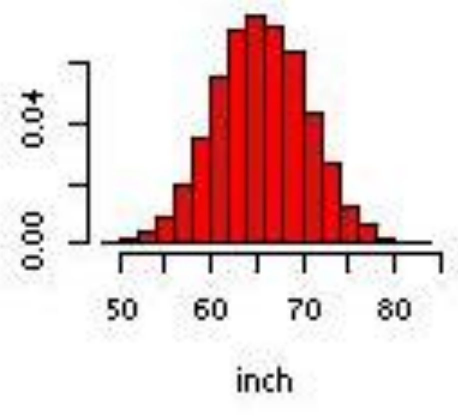
Examples

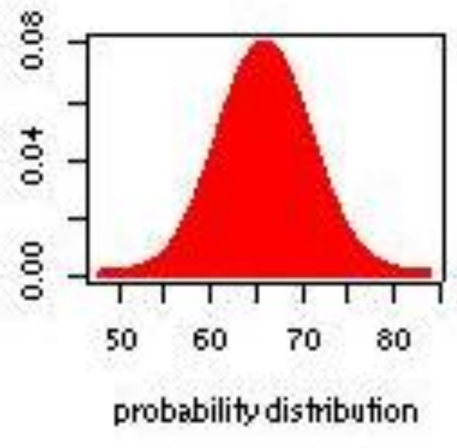
Discrete	Continuous
• # of eggs in a basket • # of kids in a class • # of Facebook likes • # of diaper changes in a day • # of wins in a season • # of votes in an election	• Weight difference to 8 decimals before and after cookie binge. • Wind speed • Water temperature • Volts of electricity

Continuous Probability Distribution

- Suppose we measure height of students in this class. If we “discretize” by rounding to the nearest feet, the discrete probability histogram is shown on the left. Now if height is measured to the nearest inch, a possible probability histogram is shown in the middle. We get more bins and much smoother appearance. Imagine we continue in this way to measure height more and more finely, the resulting probability histograms approach a smooth curve shown on the right.

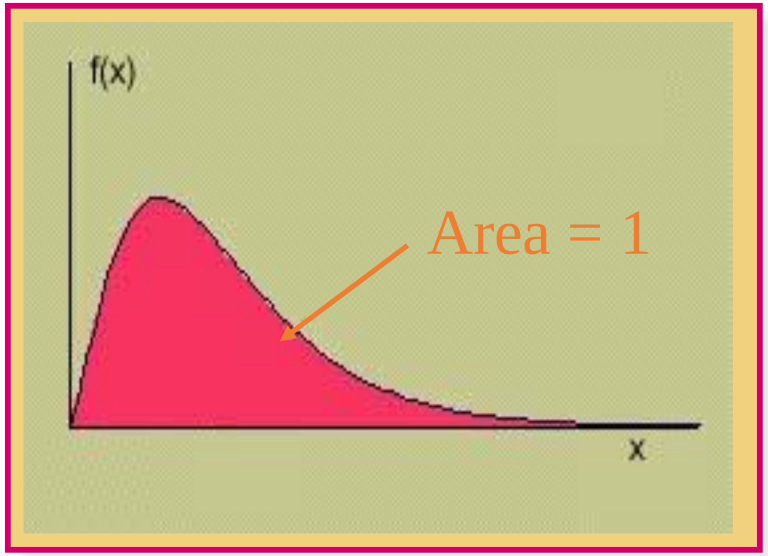






Cont. Continuous Probability Distribution

- **Probability distribution** describes how the probabilities are distributed over all possible values. A **probability distribution** for a **continuous random variable *x*** is specified by a mathematical function denoted by *f(x)* which is called the **probability density function (PDF).** The graph of a density function is a smooth curve.



Probability distributions

$$F(x) = P(X \leq x) = \sum_i P(x_i)$$

$$F(x_1) = P(-\infty \leq x \leq x_1) = \int_{-\infty}^{x1} f(x)dx$$

$$P(x_1 \leq x \leq x_2) = F(x_2) - F(x_1)$$

Properties of PDFs

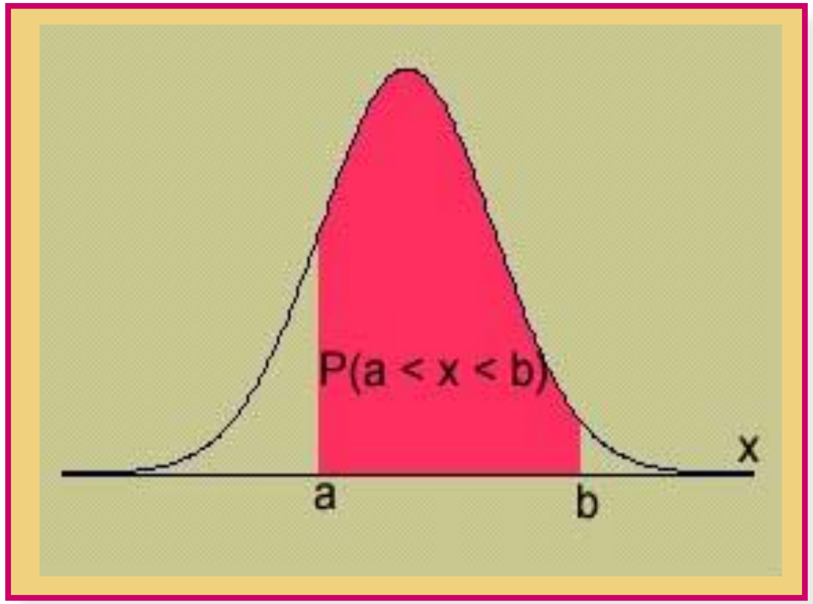
1) $f(x) \geq 0$

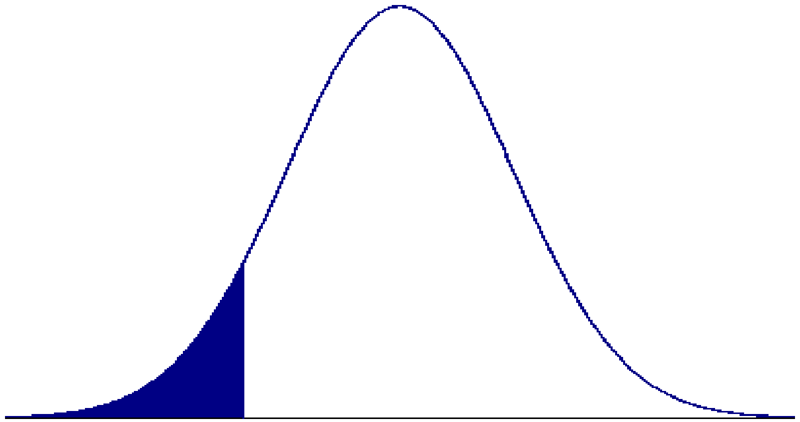
2) $\int_{-\infty}^{\infty} f(x)\,dx = 1$

3) $\text{Prob}(x < b) = \text{Prob}(x \leq b) = \int_{-\infty}^{b} f(x)\,dx$

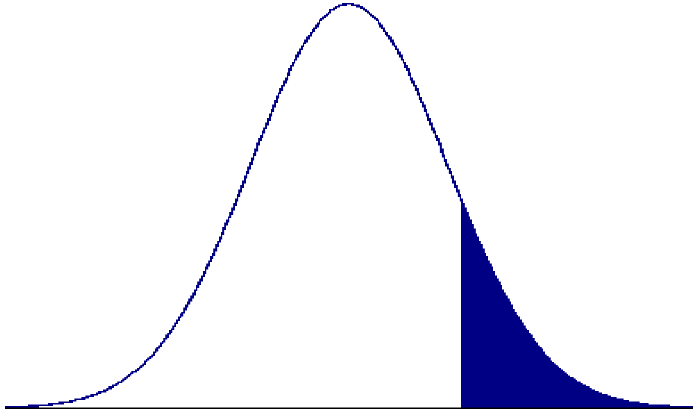
4) $\text{Prob}(a < x < b) = \text{Prob}(a \leq x \leq b) = \int_{a}^{b} f(x)\,dx$

5) $\text{Prob}(x = a) = 0$





a



b

Notice that for a continuous random variable *x*,

$$P(x = a) = 0$$

for any specific value *a* because the “area above a point” under the curve is a line segment and hence has 0 area. Specifically this means

$$P(x < a) = P(x \leq a)$$

$$P(a < x < b) = P(a \leq x < b) = P(a < x \leq b) = P(a \leq x \leq b)$$

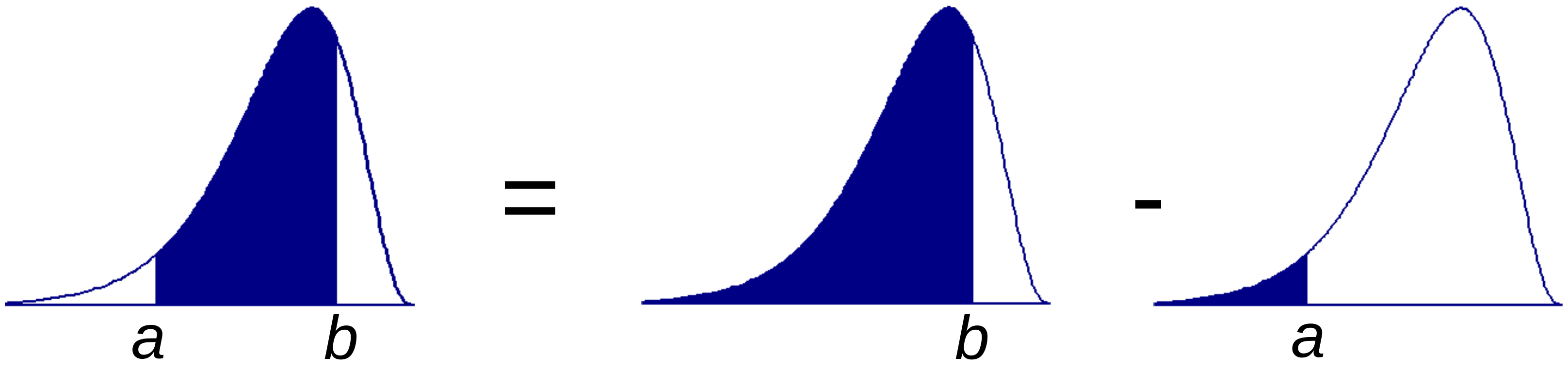
Method of Probability Calculation

The probability that a continuous random variable *x* lies between a lower limit *a* and an upper limit *b* is

$P(a<x<b)$ = (cumulative area to the left of b) –

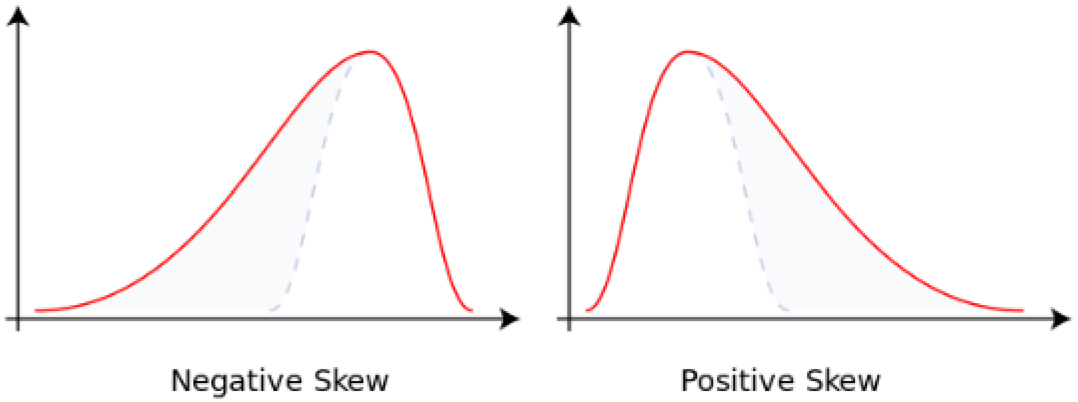
(cumulative area to the left of a)

$= P(x < b) - P(x < a)$



Skewness

- **skewness** is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. The skewness value can be positive or negative, or undefined.



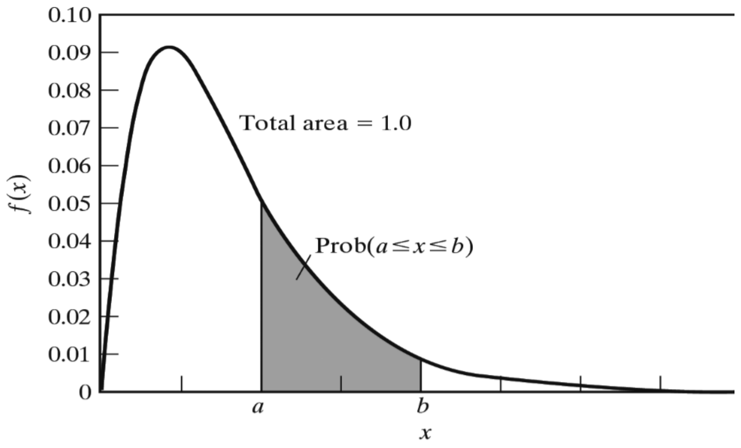


Figure 3.7

Continuous probability density function.

Skewness coefficient

- Used to evaluate high or low data points - flood or drought data

$$\text{Skewness} \rightarrow \frac{\mu_3}{\sigma^3} \rightarrow \text{third central moment}$$

$$C_s = \frac{n}{(n-1)(n-2)} \frac{\sum (x_i - \bar{x})^3}{s_x^3}$$

$$\text{Coeff of Var} = \frac{\sigma}{\mu}$$

Skewed data-Long right tail

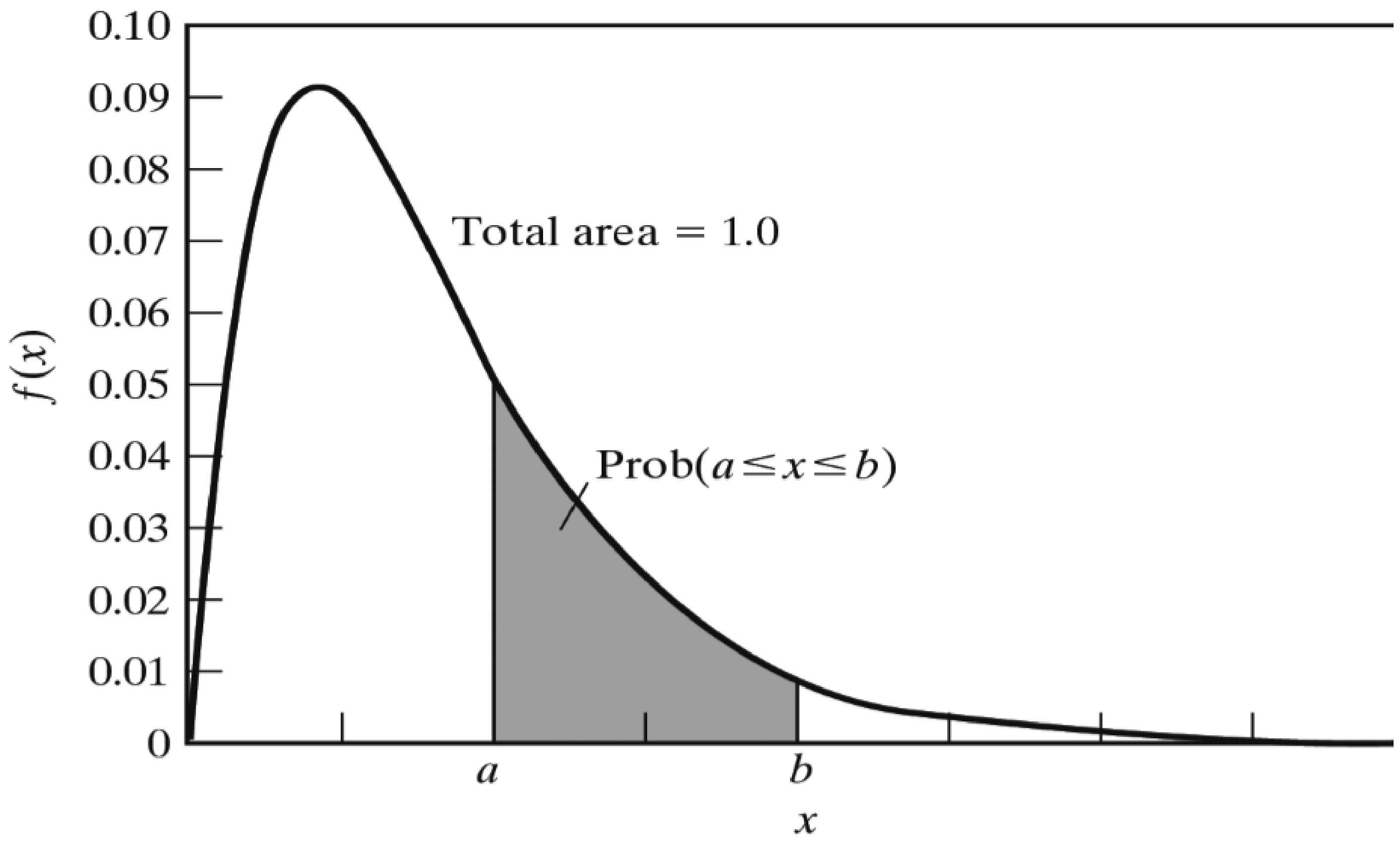


Figure 3.7

Continuous probability density function.

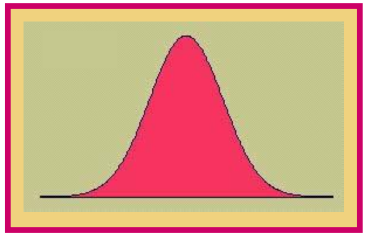
Continuous Probability Distributions

- There are many different types of continuous random variables
- We try to pick a model that
  - **Fits the data well**
  - **Allows us to make the best possible inferences using the data.**
- One important continuous random variable is the **normal random variable**.

Major distributions

- Binomial - P (x successes in n trials)
- Exponential - decays rapidly to low probability
- Normal - Symmetric based on μ and σ
- Lognormal - Log data are normally distributed
- Gamma - skewed distribution
- Log Pearson III - skewed and recommended by the IAC on water data - most used

The Normal Distribution



The formula that generates the normal probability distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad \text{for } -\infty < x < \infty$$

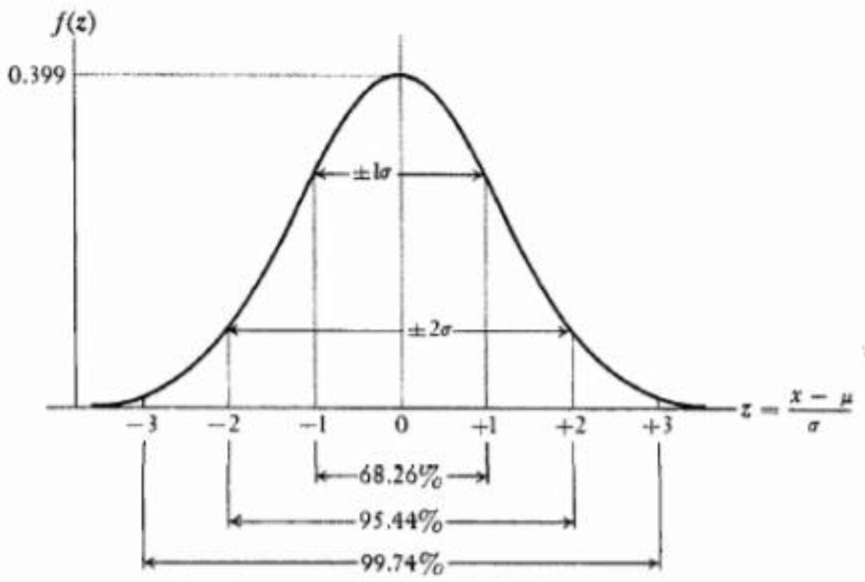
$$e = 2.7183 \qquad \pi = 3.1416$$

μ and σ are the population mean and standard deviation.

Two parameters, mean and standard deviation, completely determine the Normal distribution. The shape and location of the normal curve changes as the mean and standard deviation change.

Why normal distribution!

- The normal distribution is the most widely known and used of all distributions. Because the normal distribution approximates many natural phenomena so well, it has developed into a standard of reference for many probability problems.



Why is the normal distribution useful?

- Many things actually are normally distributed, or very close to it. For example, height and intelligence are approximately normally distributed; measurement errors also often have a normal distribution

- The normal distribution is easy to work with mathematically. In many practical cases, the methods developed using normal theory work quite well even when the distribution is not normal.

- There is a very strong connection between the size of a sample N and the extent to which a sampling distribution approaches the normal form. Many sampling distributions based on large N can be approximated by the normal distribution even though the population distribution itself is definitely not normal.

Mean and Variance

- The mean or expected value:

$$\mu = E(X) = \int_{-\infty}^{\infty} x f(x)\,dx$$

- The variance and standard deviation:

$$\sigma^2 = Var(X) = \int_{-\infty}^{\infty} (x-\mu)^2 f(x)\,dx = \int_{-\infty}^{\infty} x^2 f(x)\,dx - \mu^2 = E(X^2) - \left[E(X)\right]^2$$

The standard deviation: $\sigma = \sqrt{\sigma^2}$

Estimate of moment from data

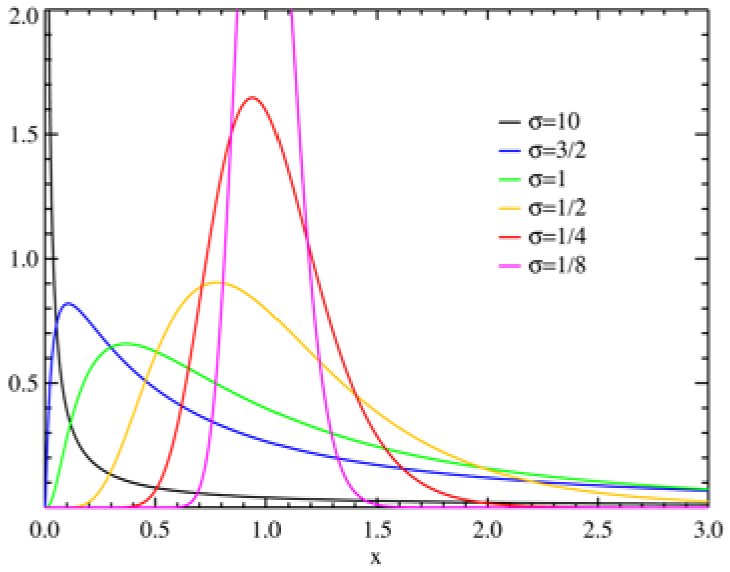
$$\bar{x} = \frac{1}{n}\sum_{i}^{n} x_i \Rightarrow \text{Mean of Data}$$

$$s_x^2 = \frac{1}{n-1}\sum (x_i - \bar{x})^2 \Rightarrow \text{Variance}$$

$$\textbf{\textit{Std Dev.}} \quad S_x = (S_x{}^2)^{1/2}$$

Lognormal distribution

- If the pdf of X is skewed, it's not normally distributed
- If the pdf of Y = log (X) is normally distributed, then X is said to be lognormally distributed.



$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(y-\mu_y)^2}{2\sigma_y^2} \right) \qquad x > 0, \textit{and } y = \log x$$

Hydraulic conductivity, distribution of raindrop sizes in storm follow lognormal distribution.

Example

The annual rainfall totals from a station, Mogadishu (Somalia), for a period of 32 years are given. Compute the annual rainfall total corresponding to 67 % & 33 % probabilities of exceedance.

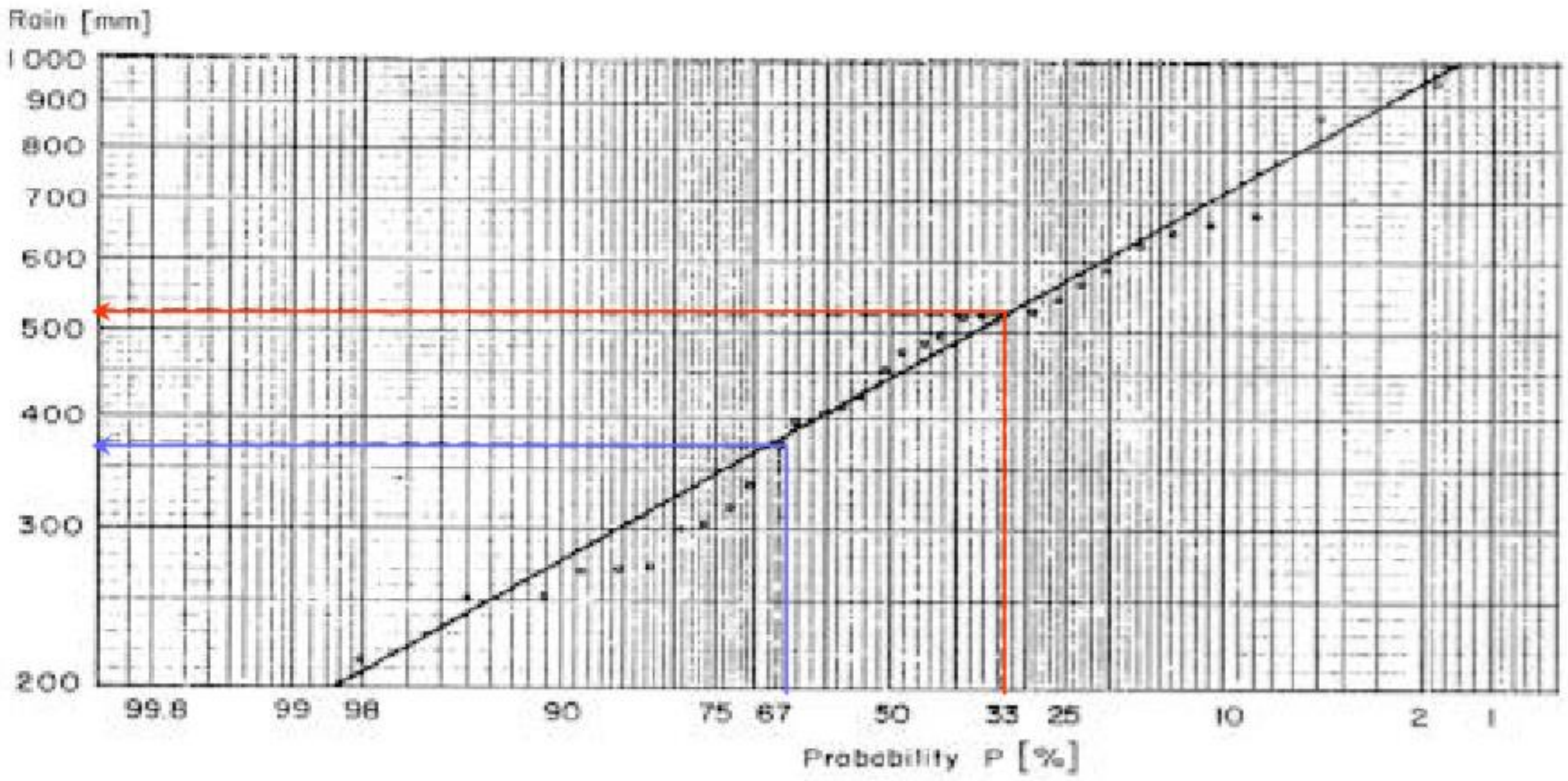
Year	1957	1958	1959	1960	1961	1962	1963	1964
Rainfall	484	529	302	403	960	453	633	489
Year	1965	1966	1967	1968	1969	1970	1971	1972
Rainfall	498	395	890	680	317	300	271	655
Year	1973	1974	1975	1976	1977	1978	1979	1980
Rainfall	371	255	411	339	660	216	594	544
Year	1981	1982	1983	1984	1985	1986	1987	1988
Rainfall	563	526	273	270	423	251	533	531

Solution

Arrange values in decreasing order

Year	R mm	m	p %	Year	R mm	m	p %	Year	R mm	m	p %
1961	960	1	1.9	1958	529	12	36.0	1976	339	23	70.2
1967	890	2	5.0	1982	526	13	39.1	1969	317	24	73.3
1968	680	3	8.1	1965	498	14	42.2	1959	302	25	76.4
1977	660	4	11.2	1964	489	15	45.3	1970	300	26	79.5
1972	655	5	14.3	1957	484	16	48.4	1983	273	27	82.6
1963	633	6	17.4	1962	453	17	51.6	1971	271	28	85.7
1979	594	7	20.5	1985	423	18	54.7	1984	270	29	88.8
1981	563	8	23.6	1975	411	19	57.8	1974	255	30	91.1
1980	544	9	26.7	1960	403	20	60.9	1986	251	31	95.0
1987	533	10	29.8	1966	395	21	64.0	1978	216	32	98.1
1988	531	11	32.9	1973	371	22	67.1				

Note: Blom formula is used in this example plot p against R on a probability paper and draw the best fit line



p = 67 % , Tr = 1.5 years , R = 371 mm
p = 33 % , Tr = 3 years , R = 531 m

Extreme value (EV) distributions

- Extreme values – maximum or minimum values of sets of data.

- Annual maximum discharge, annual minimum discharge.

- When the number of selected extreme values is large, the distribution converges to one of the three forms of EV distributions called Type I, II and III.

Frequency analysis for extreme events

Q. Find a flow (or any other event) that has a return period of T years

$$f(x) = \frac{1}{\alpha}\exp\left[-\frac{x-u}{\alpha} - \exp\left(-\frac{x-u}{\alpha}\right)\right] \qquad F(x) = \exp\left[-\exp\left(-\frac{x-u}{\alpha}\right)\right]$$

EV1 pdf and cdf

$$\alpha = \frac{\sqrt{6}s_x}{\pi} \qquad u = \bar{x} - 0.5772\alpha$$

Define a reduced variable y $y = \dfrac{x-u}{\alpha}$

$$F(x) = \exp[-\exp(-y)]$$

$$y = -\ln[-\ln(F(x))] = -\ln[-\ln(1-p)] \quad where\ p = P(x \geq x_T)$$

$$y_T = -\ln\left[-\ln\left(1-\frac{1}{T}\right)\right]$$

If you know T, you can find y_T, and once y_T is know, x_T can be computed by

$$x_T = u + \alpha y_T$$

Example

- Given annual maxima for 10-minute storms
- Find 5- & 50-year return period 10-minute storms

$$\bar{x} = 0.649\,in$$

$$s = 0.177\,in$$

$$\alpha = \frac{\sqrt{6}s}{\pi} = \frac{\sqrt{6} * 0.177}{\pi} = 0.138 \qquad u = \bar{x} - 0.5772\alpha = 0.649 - 0.5772 * 0.138 = 0.569$$

$$y_5 = -\ln\left[\ln\left(\frac{T}{T-1}\right)\right] = -\ln\left[\ln\left(\frac{5}{5-1}\right)\right] = 1.5$$

$$x_5 = u + \alpha y_5 = 0.569 + 0.138 * 1.5 = 0.78\,in$$

$$x_{50} = 1.11\,in$$

Example

- Given annual maximum rainfall, calculate 5-yr storm using frequency factor

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\}$$

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{5}{5-1}\right)\right]\right\} = 0.719$$

$$\begin{aligned} x_T &= \bar{x} + K_T s \\ &= 0.649 + 0.719 \times 0.177 \\ &= 0.78\ in \end{aligned}$$

Engineering Hydrology

110401454

Introduction

Instructor: Dr. Zeyad Tarawneh

Course Contents

Introduction, watershed and flow:

Definition, hydrologic cycle, water balance, watersheds, statistical methods in hydrology, IDF curves, measuring flow in small watersheds and water harvesting.

Hydrologic parameters:

Rainfall, evaporation, infiltration, storage, excess rainfall, SCS method (CN).

Measuring flow in large watersheds:

Hydrograph, surface and base flow, UH, synthetic hydrographs.

Course Contents

Groundwater flow:

Aquifers, Darcy law, steady flow from confined and unconfined aquifers, water table drop, well influence distance, multiple wells system, groundwater recharge.

Introduction to water resources:

Potential water sources, surface and ground storage, reservoir sizing.

Introduction

What do you observe in the image?

What the civil engineer can do?

Amman Jan 8, 2013. (Source: The Jordan Times Jan 8, 2013).

Introduction

What do you observe in the image?

Amman - Zarqa highway near Ain Ghazal intersection Jan 8, 2013.

Introduction

Hydrological useful statements:

Zarqa town resident said: the rain has stopped 1 hour ago, but the flood continued coming from higher areas. Manholes in the streets were flooded by the heavy rain causing damage to his mini-market. The last time I saw such heavy rain was in the 1970s.

Zarqa city (Source: The Jordan Times 25/11/2012)

Introduction

The word Hydrology came from the Latin combination of Hydro that means water and logy that means science. Compared to hydrology, the course fluid mechanics focuses on the physics of fluids (water) like: viscosity, shear stress, buoyancy, pressure and force, momentum conservation, energy conservation, mass conservation, etc...

Compared to hydrology, the course hydraulics focuses on the behavior of the water like: flow velocity and depth, specific energy, hydraulic jump, hydraulic sections design, flow in pipes, flow under varying head, etc...

Introduction

Hydrology is generally defined as the science that studies issues related to the water cycle and balance, the variation in precipitation and flow amounts, the land that receives precipitation, the surface and groundwater flow amounts, the distribution of the flow over the time.

Applications of the hydrology in **CE**:

- Storm water sewer design,
- Water harvesting,
- Culvert design.

Introduction

Ancient hydrology in Jordan!

Jawa Dam

From Wikipedia, the free encyclopedia

The **Jawa Dam** is the remains of an ancient masonry gravity dam on Wadi Rajil at Jawa in Mafraq Governorate, Jordan, 58 kilometres (36 mi) north of Azraq. It is the oldest known dam in the world, dating back to 3000 BC. The dam was part of a water supply system that eventually consisted of other smaller dams to support the growing local town of Jawa. Therefore, the term **Jawa Dams** is sometimes used to describe the dams around Jawa. The Jawa Dam, though, is the largest of the dams and withheld the largest reservoir.[1][2][3]

Svend Helms, who directed an excavation of the area in 1970, determined that the Jawa Dam was used to harvest rainwater. After winter precipitation runoff was diverted from Wadi Rajil, it was transferred through a small canal to a depression in the ground that was sealed off with a rock wall. This rock wall was the Jawa Dam; it had a 2-metre (6.6 ft) thick core of tampered clay, ash and soil. The core was surrounded with basalt stone walls. Loam and soil were placed at the downstream side of the dam to strengthen it and an impervious blanket was placed on the upstream heel to prevent leaks. On top of this blanket, pervious rock-fill was placed to help release water and drain the reservoir.[1][4] The dam was later heightened by 1–2 metres (3.3–6.6 ft) and its core expanded at the same time to 7 metres (23 ft) thick to further strengthen it.[2]

Over time, other dams, weirs and small canals were built in Jawa to expand the system and increase the water supply. Weirs eventually diverted water into a system of ten reservoirs for farming, herding and human consumption. The Jawa Dam's reservoir held half of the system's combined water storage capacity. The town of Jawa was estimated to quickly reach a size of 2,000 before it collapsed.[2]

Introduction

Jawa Dam

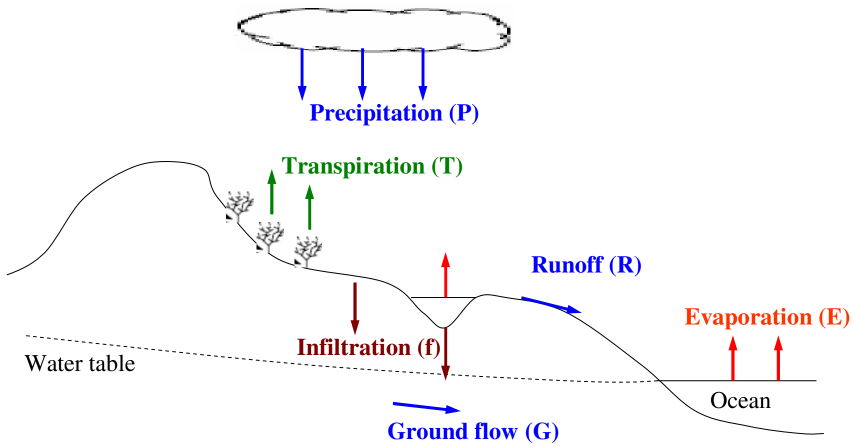
Location of Jawa Dam

Location	Jawa, Mafraq Governorate, Jordan

Coordinates	32°20′06″N 37°00′12″E
Construction began	~3000 BC
Dam and spillways	
Type of dam	Gravity, masonry
Height	4.5 m (15 ft)
Length	80 m (260 ft)
Base width	4.5–5 m (15–16 ft)
Impounds	Wadi Rajil
Reservoir	
Creates	Jawa Reservoir
Capacity	31,000 m^3 (1,100,000 cu ft) est.

Hydrologic cycle

It represents the water cycle on the earth or part of it. It is useful to study the mass balance of water over a specified region or the whole earth.

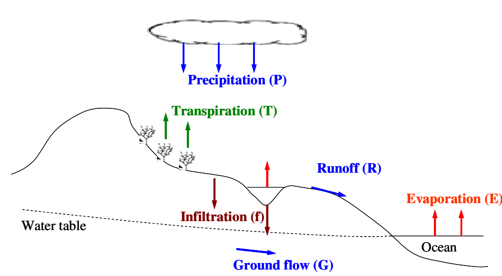


Hydrologic cycle

Water is distributed in the hydrologic cycle as follows: 97.5% as seawater and 2.5% as freshwater (including glaciers and ice caps).

Components of the cycle are:

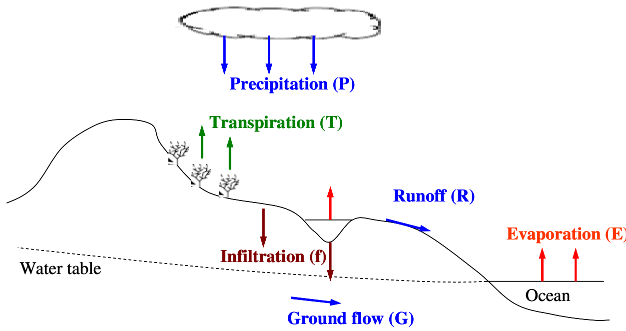
- Precipitation (P),
- Evaporation (E),
- Transpiration (T),
- Infiltration (f),
- Surface runoff (R),
- Groundwater flow (G)



Hydrologic cycle: mass balance

For given region, the change in water volumes (mass) over the time appears as a change in the storage (ΔS):

$$\Delta S = V_{in} - V_{out}$$



V_{in}: total water volume inters the region (system)

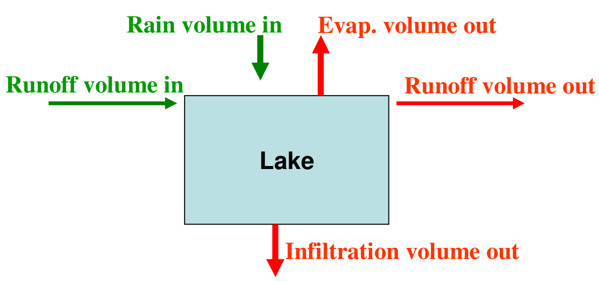
V_{out}: total water volume leaves the region (system)

Hydrologic cycle

Ex: water balance application

A dam lake of 40km^2 receives an average water flow of 0.56m^3/s for January while delivers 0.48m^3/s as leaving runoff. The cumulative precipitation for January is 45mm. The cumulative evaporation from the lake surface is 125mm and the cumulative infiltration from the lake bottom is 25mm. Calculate the change in the lake water level during January?

Soln:



Hydrologic cycle

Volume in:

$V_{R\text{-}in} = 0.56 \times 60 \times 60 \times 24 \times 31 = 1{,}499{,}904 m^3$

$V_P = 0.045 \times 40{,}000{,}000 = 1{,}800{,}000 m^3$

Volume out:

$V_{R\text{-}out} = 0.48 \times 60 \times 60 \times 24 \times 31 = 1{,}285{,}632 m^3$

$V_E = 0.125 \times 40{,}000{,}000 = 5{,}000{,}000 m^3$

$V_I = 0.025 \times 40{,}000{,}000 = 1{,}000{,}000 m^3$

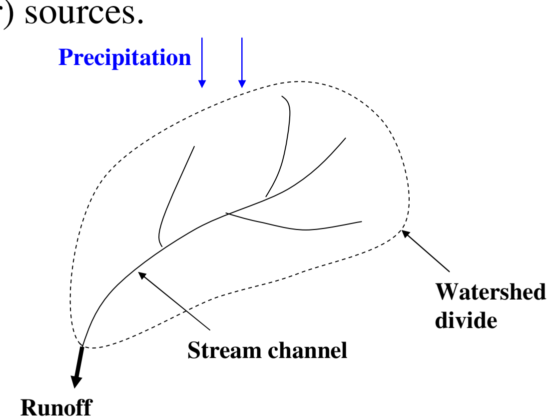
$$\Delta S = V_{in} - V_{out}$$
$$= (1{,}499{,}904 + 1{,}800{,}000) - (1{,}285{,}632 + 5{,}000{,}000 + 1{,}000{,}000)$$
$$= -\ 3{,}985{,}728 m^3$$

The change in the lake water level is a drop =

= 3,985,728 / 40,000,000 = 0.1m = 10cm.

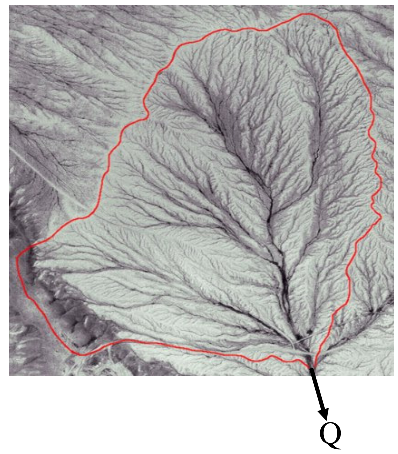
Watershed definition

The watershed is defined as the land area that contributes surface flow. The catchment is the land area that receives precipitation. The basin is usually large and contributes flow from surface and subsurface (groundwater) sources.



Watershed delineation

Watershed delineation means to mark the watershed borders where surface flow from precipitation will evolve.



Why it is important to delineate the watershed?

Answer:

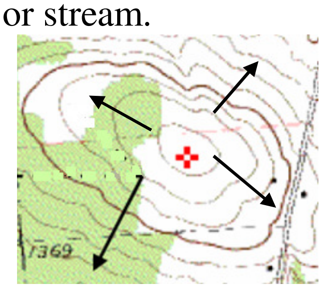
To compute Q from the watershed!

$Q \alpha A^n$ n could be 1.

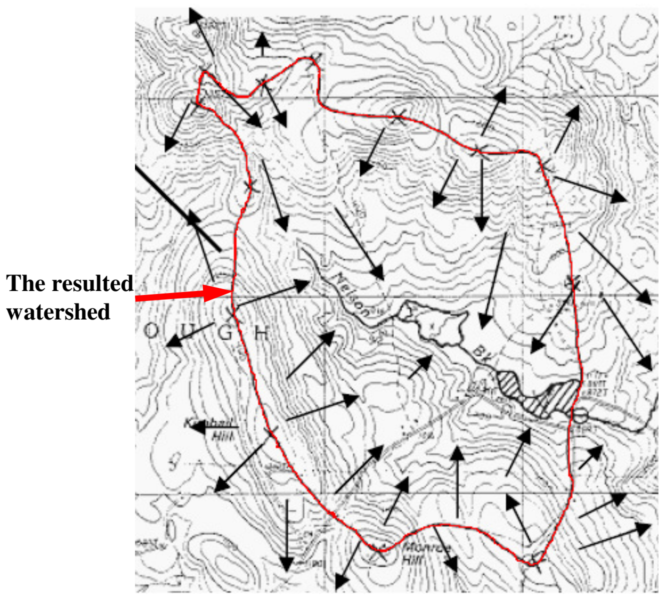
Watershed delineation

Rules:

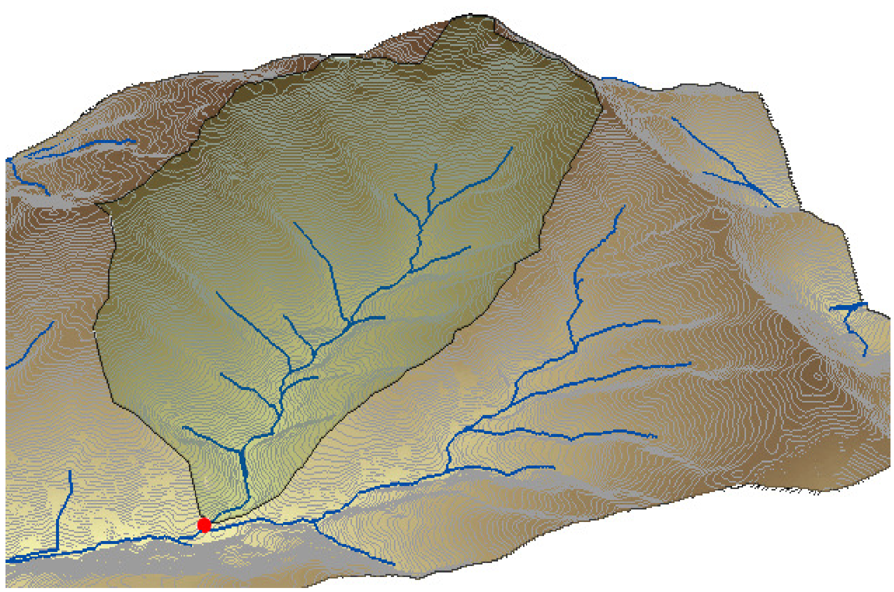
1. Locate the major stream,
2. Mark the peaks of surrounding hilltops,
3. Mark flow directions from peaks of hilltops to cross contour lines at right angle,
4. Connect the marks at peaks to include the flow direction arrows towards the major stream.



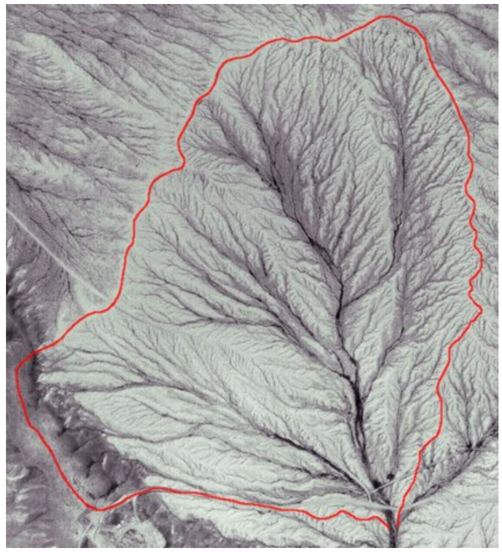
Watershed delineation: example



Watershed delineation: example



Watershed delineation using GIS



Watershed characteristics

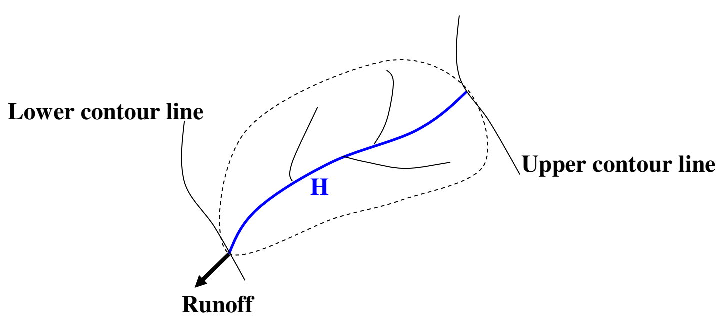
Watershed average slope:

The watershed average slope can be estimated from topographic maps as follows

$$S = \Delta E/H$$

ΔE : elevation difference along the main stream channel,

H : main stream length, map projected distance.



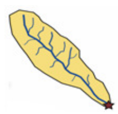
Watershed characteristics

Watershed shape:

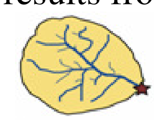
The watershed shape highly reflects the flow amount (m^3/s) and the time needed to reach the peak flow. The watershed shape is a result of the watershed slope.

In general, two types of watershed shapes are recognized:

1- Elongated watersheds: results from steep slopes.

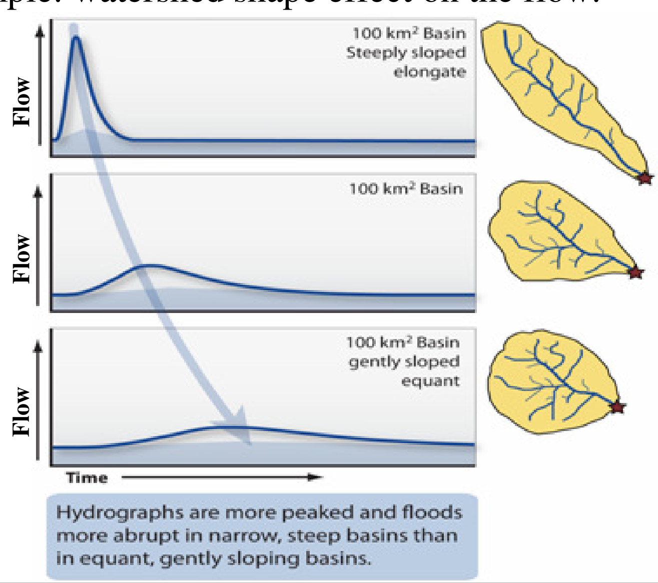


2- Equant watersheds: results from gentle slopes.



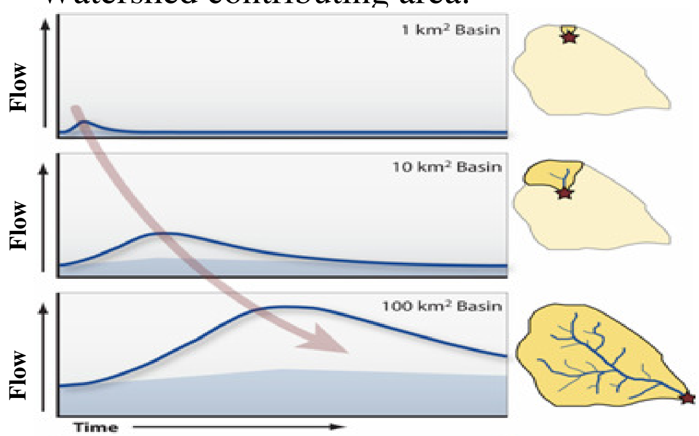
Watershed characteristics

Example: watershed shape effect on the flow.



Watershed characteristics

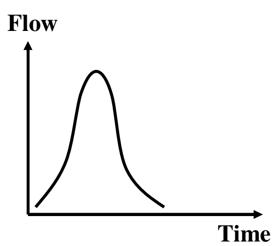
Watershed contributing area:



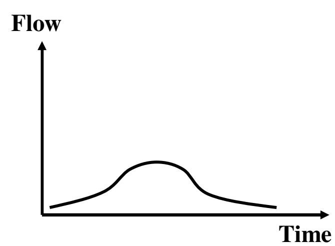
Conclusion:

As area increases, the flow amount increases, i.e. $Q \alpha A$

Watershed characteristics



Case A



Case B

Steep watershed discharges flow like case …..

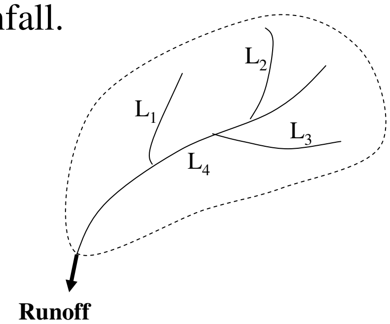
Watershed of rough surface discharges flow like case ….

Watershed characteristics

Drainage density:

The drainage density (D) is the ratio of the total length of all streams formed to the watershed area. The drainage density reflects the response of the watershed to the rainfall. It can be used to classify watersheds. Usually high D values means high and quick response (flow) of the watershed to rainfall.

$$D = \frac{\sum L}{A}$$



Watershed characteristics

Ex:

Watershed A of 4.1km^2 area has streams of 11.2km total length and watershed B of 0.58km^2 area has streams of 1.55km total length. If watershed A discharged peak flow of 1m^3/s from 30 minutes storm, estimate the peak flow resulted from watershed B when subjected to the same storm?

Soln:

D_A = 11.2 / 4.10 = 2.73

D_B = 1.55 / 0.58 = 2.67

Conclusion: $D_A \approx D_B$ (similar watersheds)

Watershed characteristics

Soln:

The flow Q is directly proportional to the area A.

$Q \propto A$ or $Q = k \times A$, or ratio $k = Q/A$ is constant.

$k_A \approx k_B$ because $D_A \approx D_B$,

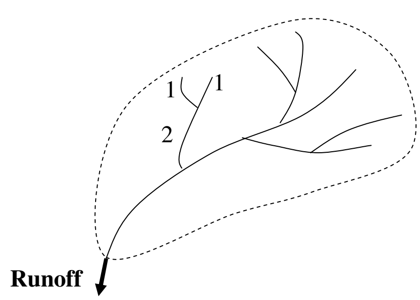
$$\frac{Q_A}{A_A} = \frac{Q_B}{A_B}$$

$Q_B = (0.58 \times 1)/4.1 = 0.141 m^3/s.$

Watershed Bifurcation

Stream order and Horton laws:

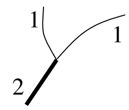
The stream order is used to classify watersheds. The order 1 is assigned to the smallest stream in the watershed, the order 2 is assigned to the next larger stream, and so on. The Horton laws can be used for computational purposes.



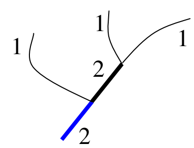
Watershed Bifurcation

Stream ordering rules:

When 2 streams of the same order (order i) are joined, the stream formed has the order of i + 1.



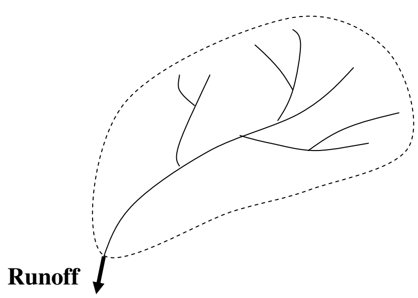
When a stream of order i meets a stream of order i + 1, then the stream formed has the order i + 1.



Watershed Bifurcation

Ex:

For the following watershed, order all streams and estimate the principal stream order.

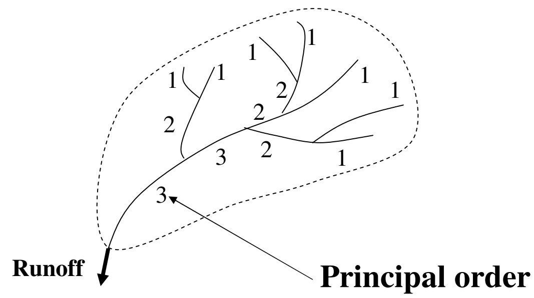


Watershed Bifurcation

Soln:

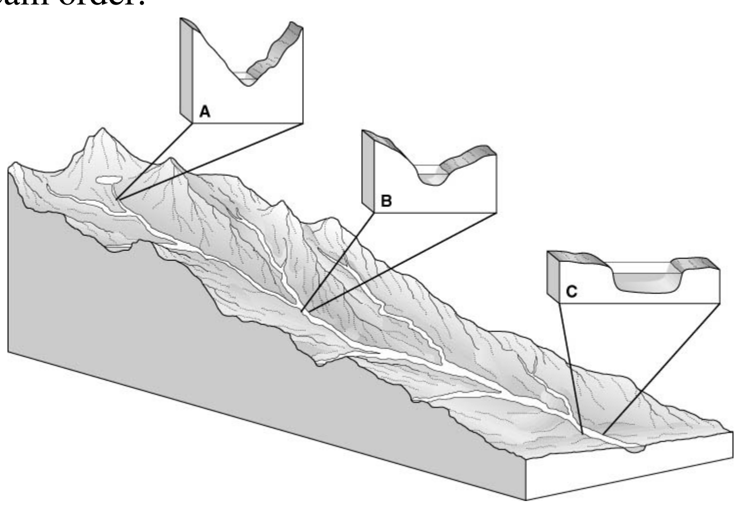
The first streams are labeled by the order 1, finish the rest using the rules mentioned previously. The principal order (k) = the largest order resulted.

$k = 3$



Watershed Bifurcation

Changes in the watershed stream properties versus the stream order.



Watershed classification

Horton laws of streams:

Law of stream number (Bifurcation ratio):

$$\frac{N_i}{N_{i+1}} = R_n \longrightarrow N_i = R_n^{k-i}$$

where k is the principal stream order.

Law of stream length

$$\frac{L_{i+1}}{L_i} = R_L \longrightarrow L_i = L_1 R_L^{i-1}$$

Watershed characteristics

Exercise:

A watershed of 5.71km^2 area has principal stream order of 4. If streams of orders 3 and 4 have 1.23km and 0.45km total length respectively, compute the watershed drainage density?

What is the length of streams of order 6?

Statistical methods in hydrology

The design of surface water systems depends on natural hydrologic variable parameters like: precipitation, runoff, humidity, wind speed, etc. Such parameters are random variables.

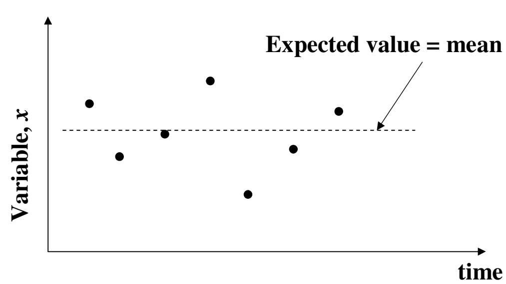
To handle such hydrologic random variables, statistical methods like the expectation, the variance, probability distribution functions, and frequency analysis are used. Such useful statistical methods will enable us to obtain the exceedance probability and the return period for design purposes, constructing IDF curves for computing peak flows for sewer sizing.

Statistical methods in hydrology

The expected value:

Given a historical record of hydrologic variable (X), for example the precipitation over n years, then the expected value (mean or average) of the variable is estimated as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

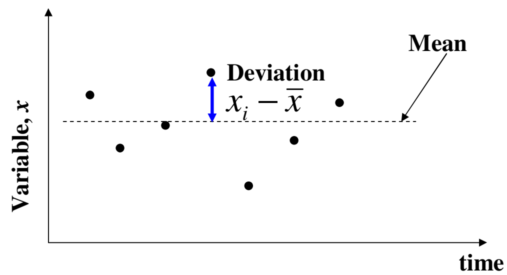


Statistical methods in hydrology

The variance and standard deviation:

Given a historical record of hydrologic variable (X), for example the precipitation over n years, then the variance is the squared deviation of the variable about its expected value (mean or average):

$$V = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2$$



The standard deviation $S = \sqrt{V}$

Statistical methods in hydrology

Example:

Given a historical record of rainfall depths (x) for years 1995 – 2010 at gauging station in Jordan. Estimate the mean and the standard deviation of the rainfall depth?

Year	Rainfall (mm)	Year	Rainfall (mm)
1995	212	2003	188
1996	123	2004	141
1997	156	2005	197
1998	225	2006	180
1999	134	2007	96
2000	175	2008	150
2001	237	2009	207
2002	249	2010	167

Statistical methods in hydrology

Soln: $n = 16$

Year	x_i	Year	x_i
1995	212	2003	188
1996	123	2004	141
1997	156	2005	197
1998	225	2006	180
1999	134	2007	96
2000	175	2008	150
2001	237	2009	207
2002	249	2010	167

The rainfall expected value (mean) =

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{16}\times 2837 = 177.3 \text{ mm}$$

Statistical methods in hydrology

Soln: $n = 16$

Year	x_i	$(x_i - \bar{x})^2$	Year	x_i	$(x_i - \bar{x})^2$
1995	212	1203.2	2003	188	114.2
1996	123	2949.8	2004	141	1318.6
1997	156	454.2	2005	197	387.6
1998	225	2274.1	2006	180	7.2
1999	134	1876	2007	96	6611.7
2000	175	5.3	2008	150	746
2001	237	3562.6	2009	207	881.3
2002	249	5139.1	2010	167	106.3

The standard deviation $S = \sqrt{V}$

$$S = \sqrt{V} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} = 42.9 \text{ mm}$$

Statistical methods in hydrology

Probability analysis of hydrologic variables:

For design of water systems, given the exceedance probability of rainfall or flow random variables, the design rainfall or flow can be obtained. The exceedance probability can be estimated by plotting the cumulative probability distribution.

Examples from CE applications:

- Design flow for culverts,
- Design rain for collection systems (Sewers).

Statistical methods in hydrology

Obtaining the design value:

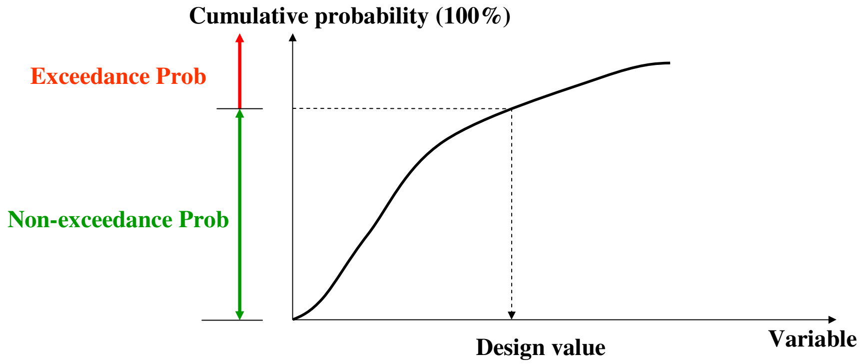
Assume the task is to design a culvert as shown. The question is: given flow values from weir, what is the value of Q_{design}?

Flow rate (m^3/s)
2.1
1.4
8.8
4.3
0.9
3.9

Statistical methods in hydrology

Obtaining the design value:

After drawing the cumulative probability and given the exceedance probability (failure probability: 5% or 10% as provided by the project owner), the design value can be obtained.



Statistical methods in hydrology

The computation of cumulative probability:

The exceedance probability can be estimated by plotting the cumulative probability distribution of the variable (rainfall or flow). Since the exact probability distribution function of the variable is unknown, the plotting position equations can be used to plot the empirical cumulative distribution of the variable.

One of the common equations to plot the empirical distribution is the **Weibull** plotting position equation.

Statistical methods in hydrology

The **Weibull** plotting position equation computes the non-exceedance probability $P(X \leq x)$ as:

$$P(X \leq x) = \frac{m}{n+1}$$

$P(X \leq x)$: probability of observing variable $\leq$ specified value x.
m: is data rank (lowest to highest).
n: record length.

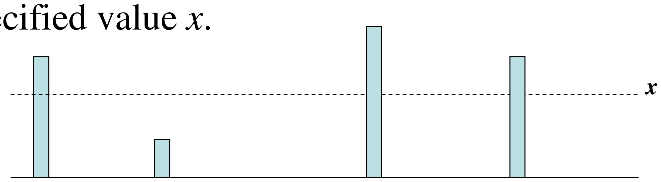
The probability $P(X > x) = 1 - P(X \leq x)$ is the exceedance probability.

Statistical methods in hydrology

Given the exceedance probability $P(X > x)$, the return period T of the hydrologic variable that exceeds specified value (x) is:

$$T = \frac{1}{P(X > x)}$$

The return period defines on average how frequent or often the variable X will take time to exceed the specified value x.



Statistical methods in hydrology

Ex:

Annual rainfall at gauging station is recorded for years 1995 – 2010. Plot the distribution of the rainfall. Assuming that the design storm is 210mm, how frequent such rainfall storm is?

Year	Rainfall (mm)	Year	Rainfall (mm)
1995	**212**	**2003**	**188**
1996	**123**	**2004**	**141**
1997	**156**	**2005**	**197**
1998	**225**	**2006**	**180**
1999	**134**	**2007**	**96**
2000	**175**	**2008**	**150**
2001	**237**	**2009**	**207**
2002	**249**	**2010**	**167**

Statistical methods in hydrology

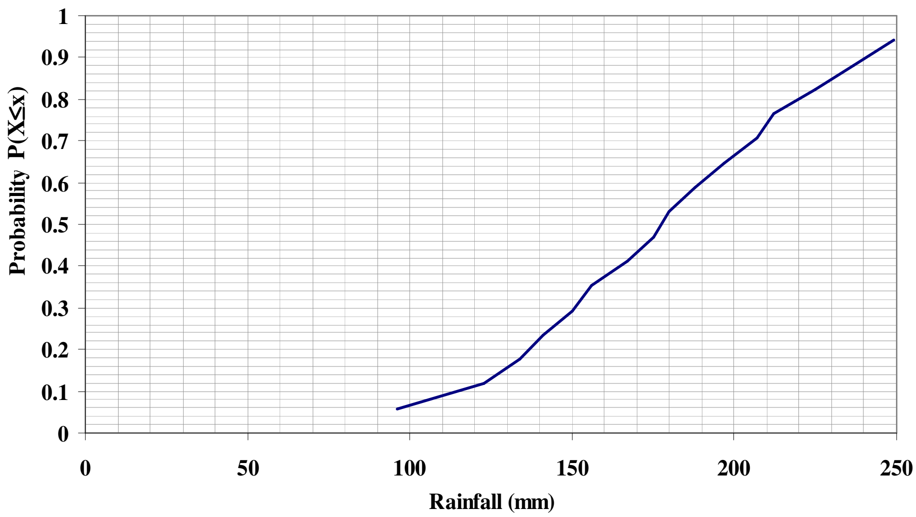
Soln: Arrange data from the lowest to highest. Rank the arranged data, and use the Weibull equation to calculate probability. $n = 16$.

Sample calculation: for $x = 96$, m = 1, then $P(X \leq x) = 1/(16+1)$
$= 0.059$.

Rank (m)	Rainfall (x)	$P(X \leq x)$	Rank (m)	Rainfall (x)	$P(X \leq x)$
1	96	0.059	9	180	0.529
2	123	0.118	10	188	0.588
3	134	0.176	11	197	0.647
4	141	0.235	12	207	0.706
5	150	0.294	13	212	0.765
6	156	0.353	14	225	0.824
7	167	0.412	15	237	0.882
8	175	0.471	16	249	0.941

Statistical methods in hydrology

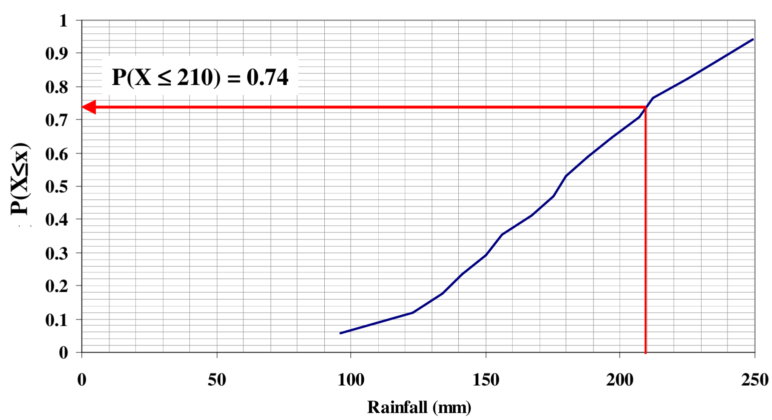
The probability distribution of the annual rainfall.



Statistical methods in hydrology

To find T for the design storm (210mm), then

P(X > *x*) = 1 – 0.74 = 0.26 and T = 1/0.26 = 3.86 ≈ 4years.



Question: estimate the design storm that being exceeded 40% of time?

Statistical methods in hydrology

Intensity Duration Frequency (IDF) curves:

Are set of curves that relate the maximum rainfall intensity (i) of a storm versus the duration (d) and the storm frequency (Return period: T years).

The rainfall intensity is defined as the ratio of the rainfall depth (mm) to the duration (hr),

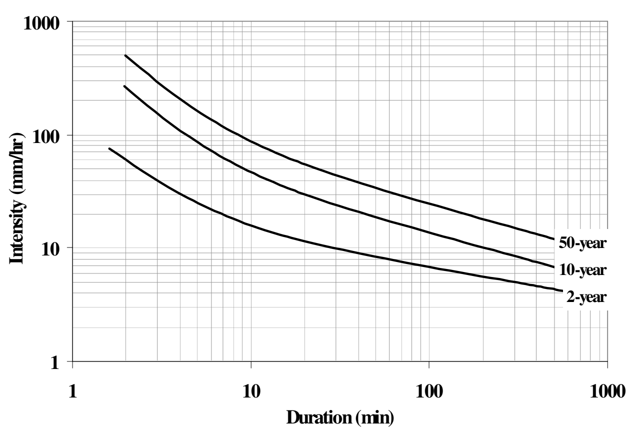
$$i(mm/hr) = \frac{x(mm)}{d(hr)}$$

Such curves are useful for computing the peak flow from small watersheds using the rational method.

Statistical methods in hydrology

IDF curves:

Are set of curves that relate the maximum rainfall intensity (i) of a storm versus the duration (d) and the storm frequency (T years).



Statistical methods in hydrology

To estimate the maximum storm intensity, we need at first to determine the maximum rainfall depth. The theoretical model that fits the distribution of the maximum rainfall depth of a given duration is the extreme value distribution type 1 (Gumbel distribution).

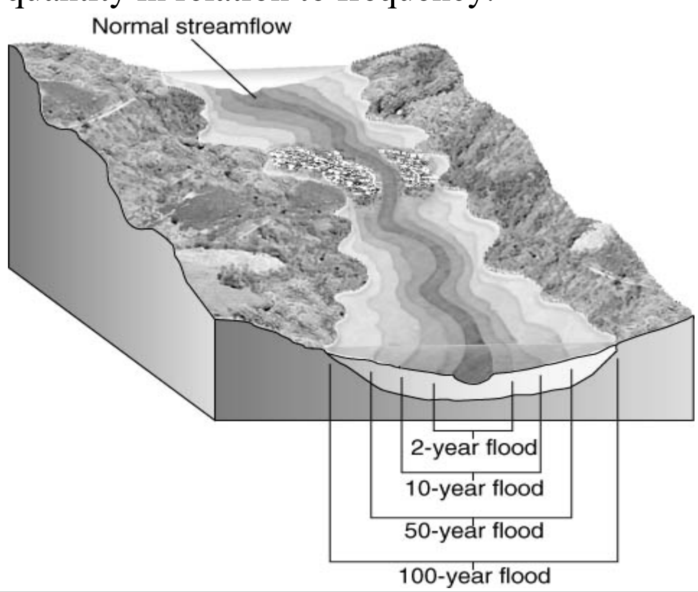
$$P(X \le x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{x-u}{\alpha}\right]\right)\right]$$

α and u are the model parameters.

$$\alpha = \frac{\sqrt{6}\,S}{\pi} \qquad u = \bar{x} - 0.5772\,\alpha$$

Statistical methods in hydrology

Flow quantity in relation to frequency.



Statistical methods in hydrology

Ex:

Plot the theoretical distribution for the following 15-minute extreme rainfall depths.

Year	15-minute extreme rainfall depth (mm)
2000	12
2001	17
2002	7
2003	14
2004	27
2005	9
2006	13
2007	18
2008	8
2009	15
2010	11

Statistical methods in hydrology

Ex:

$\bar{x} = 13.72mm$ $\qquad S = 5.64mm$

$$\alpha = \frac{\sqrt{6} \times 5.64}{\pi} = 4.4$$

$$u = 13.72 - 0.5772 \times 4.4 = 11.18$$

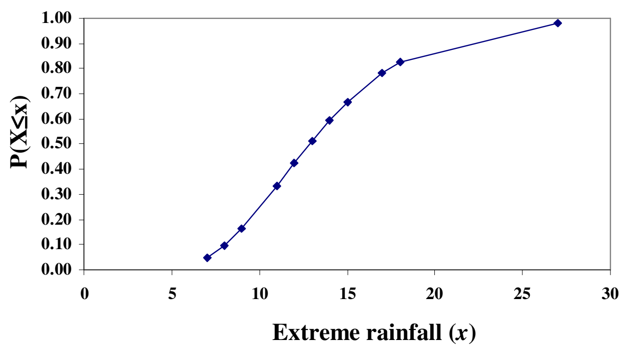
$$P(X \le x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{x-u}{\alpha}\right]\right)\right]$$

Statistical methods in hydrology

Ex:

$$P(X \leq 7mm) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{7-11.18}{4.4}\right]\right)\right] = 0.08$$

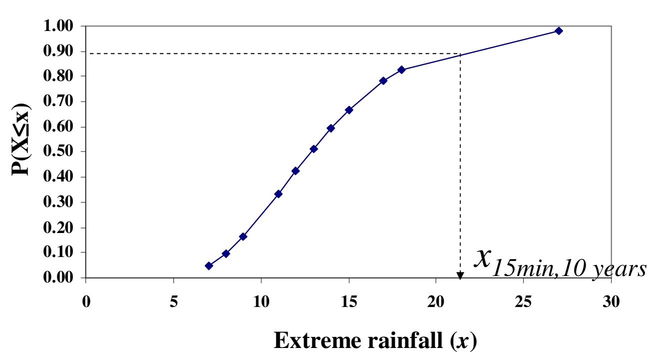
x	P(X ≤ x)
7	0.08
8	0.13
9	0.19
11	0.35
12	0.44
13	0.52
14	0.59
15	0.66
17	0.77
18	0.81
27	0.97



Statistical methods in hydrology

Question: what is the amount of the extreme rainfall depth that is associated to 15 mins duration and return period of 10 years, i.e. $x_{15min,10\ years}$

Answer: use the probability plot



Statistical methods in hydrology

The past question can be also answered computing the quantile ($x_{d,T}$) using the frequency factor (K_T) of the Gumbel distribution as follows:

$$x_{d,T} = \bar{x}_d + K_T\, S_d$$

$x_{d,T}$: extreme rainfall depth for storm of duration d and frequency T years.

$\bar{x}_d$ and S_d: mean and standard deviation of the extreme rainfall depths for storm of duration d (from records).

K_T: frequency factor of the Gumbel distribution.

$$K_T = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \mathbf{ln}\left(\mathbf{ln}\left[\frac{T}{T-1}\right]\right)\right]$$

Statistical methods in hydrology

Ex:

For the past 15-minute extreme rainfall depths, estimate the amount of the 15-minute rainfall depth associated to the 10-year return period

Year	15-minute extreme rainfall depth (mm)
2000	12
2001	17
2002	7
2003	14
2004	27
2005	9
2006	13
2007	18
2008	8
2009	15
2010	11

Statistical methods in hydrology

Ex:

$$K_T = K_{10} = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \mathbf{ln}\left(\mathbf{ln}\left[\frac{10}{10-1}\right]\right)\right] = 1.3$$

From the historical data

$$\bar{x}_d = \bar{x}_{15} = 13.72mm \qquad S_d = S_{15} = 5.64mm$$

then the amount of 15-min rainfall at T = 10 years is

$$x_{d,T} = \bar{x}_d + K_T\, S_d$$

$$x_{15\,\mathbf{min,}10\,year} = \bar{x}_{15} + K_{10}\, S_{15} = 13.72 + 1.3 \times 5.64$$

$$x_{15\,\mathbf{min,}10\,year} = 21mm$$

Statistical methods in hydrology

Ex:

A watershed discharges extreme flows of $3m^3/s$ and $4.4m^3/s$ from 30 minutes storm of 10 and 20 years return periods, compute the extreme flow that is associated to the 30 minutes storm but of 50 years return period?

Statistical methods in hydrology

Steps to construct the IDF curves:

1. From precipitation records, for each year extract the max rainfall depths for durations: 5mins, 10, 15, 30mins, 1hr, 2, 6, and 24hrs.
2. Estimate the mean and standard deviation of max rainfall depths at the durations listed above.
3. Using the extreme value distribution estimate the frequency factor K_T and estimate the amount of rainfall depth ($x_{d,T}$) for durations listed at return periods of 2 years, 5, 10, 25, 50, and 100 years.
4. Correct the rainfall depths at the 2-year and 5-year return period by multiplying with 0.88 for the 2-year and 0.96 for the 5-year return period.

Statistical methods in hydrology

Steps to construct the IDF curves:

6. Calculate the rainfall intensity (i) in mm/hr units as:

$$i(mm/hr) = \frac{x_{d,T}}{d}$$

7. Plot the IDF curves. Place storm duration (d) at log scale on x-axis. Place the intensity (i) at log scale on the y-axis.

Statistical methods in hydrology

Ex:

Construct the 5-year IDF curve for the following max rainfall depths of 15-min and 60-min duration.

Year	15-min max rainfall	60-min max rainfall
2000	24	45
2001	30	75
2002	20	34

Soln:

for 15-min, $\bar{x}_{15} = 24.7mm \qquad S_{15} = 5mm$

for 60-min, $\bar{x}_{60} = 51.3mm \qquad S_{60} = 21.2mm$

$$K_5 = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left(\ln\left[\frac{5}{5-1}\right]\right)\right] = 0.72$$

Statistical methods in hydrology

Ex:

Soln: $x_{d,T} = \bar{x}_d + K_T S_d$

For 15-min, $x_{15,5}$ = 24.7 + 0.72×5 = 28.3mm

The corrected $x_{15,5}$ = 0.96×28.3 = 27.2mm,

$$i = \frac{27.2}{(15/60)} = 108.8mm/hr$$

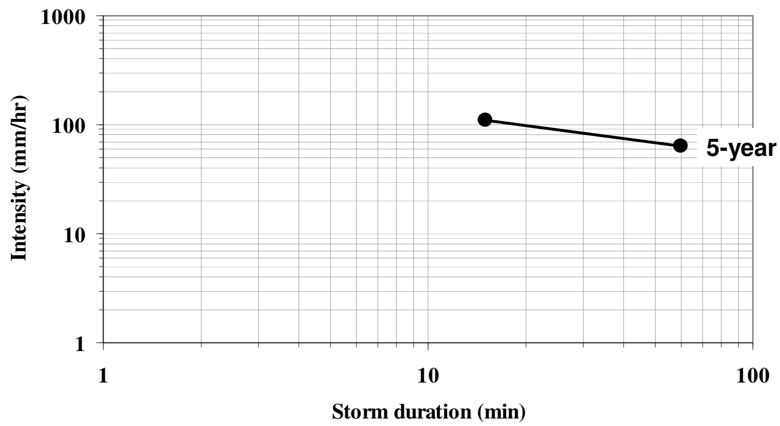
For 60-min, $x_{60,5}$ = 51.3 + 0.72×21.2 = 66.6mm

The corrected $x_{60,5}$ = 0.96×66.6 = 64mm,

$$i = \frac{64}{(60/60)} = 64mm/hr$$

Statistical methods in hydrology

Ex: Result IDF for 5 years return period.



Micro-scale basin: computing the runoff

The surface runoff (flow) from small watersheds can be computed using the rational method benefiting of the IDF curves. In urban hydrology, the rational method is used to estimate the peak runoff for storm sewer design. The peak flow (m^3/s) is:

$$Q = 0.278\, C\, i\, A$$

C : runoff coefficient,

i : storm intensity (mm/h) obtained from IDF curves,

A : watershed contributing area (km^2).

Land Use or Type	C Value
Agriculture	
Bare Soil	0.20-0.60
Cultivated Fields (sandy soil)	0.20-0.40
Cultivated Fields (clay soil)	0.30-0.50
Grass	
Turf, Meadows	0.10-0.40
Steep Grassed Areas	0.50-0.70
Woodland	
Wooded Areas with Level Ground	0.05-0.25
Forested Areas with Steep Slopes	0.15-0.40
Bare Areas, Steep and Rocky	0.50-0.90
Roads	
Asphalt Pavement	0.80-0.90
Cobblestone or Concrete Pavement	0.60-0.85
Gravel Surface	0.40-0.80
Native Soil Surface	0.30-0.80
Urban Areas	
Residential, Flat	0.40-0.55
Residential, Moderately Steep	0.50-0.65
Commercial or Downtown	0.70-0.95

Micro-scale basin: computing the runoff

The rational method is usually used conditioning to:

- the watershed area is small ($< 3km^2$).
- the watershed is nearly flat.
- the storm duration is ≥ the time of concentration.

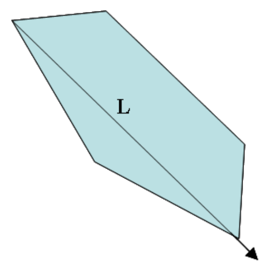
If the conditions mentioned above are not applicable, then the accuracy of the rational method is questionable. In that case the unit hydrograph, synthetic hydrographs and SCS method are used to estimate the peak runoff (will be discussed later).

Micro-scale basin: computing the runoff

The time of concentration t_c:

For a given watershed, the time of concentration is defined as the time needed such that the whole watershed discharges flow. It is the longest time needed for a water drop to travel through the watershed to the final drainage point. Using the Kerby-Kirpich method, t_c in **minutes**:

$$t_c = \frac{0.828(L \times n)^{0.467}}{S^{0.235}}$$

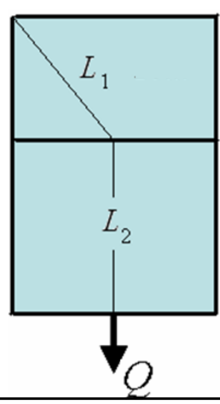


n: Roughness of surface
L: flow path distance (m)
S: surface slope

Micro-scale basin: computing the runoff

Ex:

For the watershed shown below, compute (estimate) the peak flow from a storm of 2 years return period that lasts for 20mins (IDF curves given).

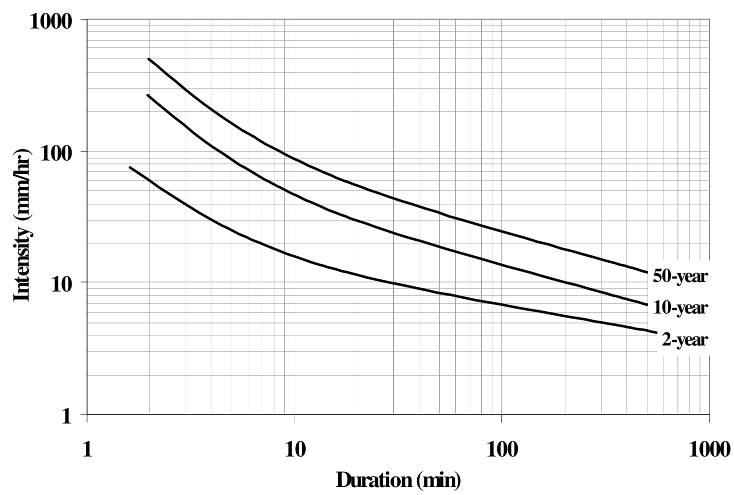


$C_1 = 0.8$, $A_1 = 40000\ \text{m}^2$
$S_1 = 1\%$, $n_1 = 0.025$, L_1=220m

$C_2 = 0.9$, $A_2 = 50000\ \text{m}^2$
$S_2 = 1.5\%$, $n_2 = 0.03$, L_2=250m

Micro-scale basin: computing the runoff

IDF curves.



Micro-scale basin: computing the runoff

Soln:

The time of concentration t_{c1} from sub-watershed 1=

$$= 0.828\times(220\times0.025)^{0.467}/0.01^{0.235} = 5.4 \text{ mins.}$$

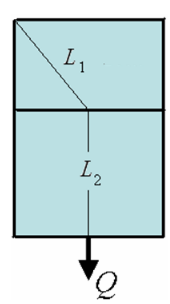
The time of concentration t_{c2} from sub-watershed 2=

$$= 0.828\times(250 \times0.03)^{0.467}/0.015^{0.235} = 5.7 \text{ mins.}$$

The time of concentration from the whole watershed =

$$t_c = 5.4 + 5.7 = 11.1 \text{ mins.}$$

Why both times have been added?



Micro-scale basin: computing the runoff

Soln:

The average watershed C =

$$C = \frac{(0.8 \times 40000) + (0.9 \times 50000)}{90000} = 0.86$$

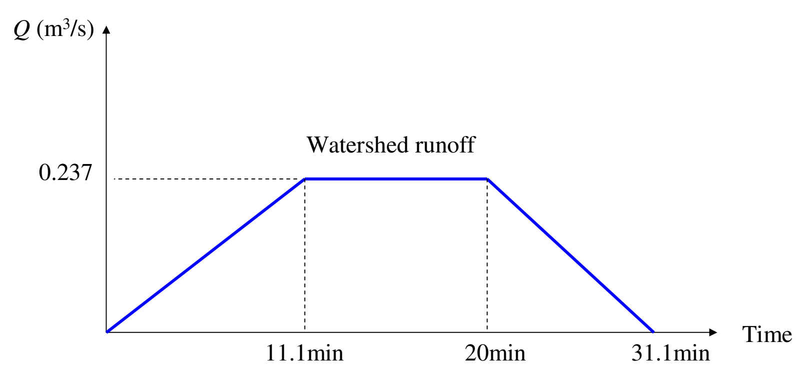
For t_c = 11.1mins < storm duration (20mins), and for T = 2 years then from the IDF-curves the storm intensity i = 11mm/h.

The peak flow $Q = 0.278 \times 0.86 \times 11 \times 0.09 = 0.237 m^3/s$

Micro-scale basin: computing the runoff

Soln:

The resulted flow hydrograph (the hydrograph is defined as flow profile over the time).



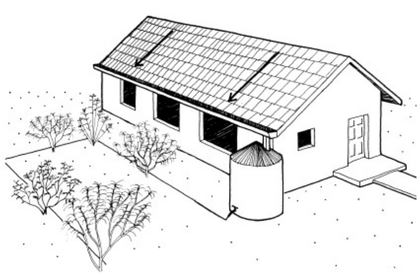
Micro-scale rainwater harvesting

Rainwater falls on small catchments (surfaces) will finally generate clean water runoff (flow) that can be collected as potential water source. Such small catchments can be: house rooftop, paved street or parking lot. The quality of such collected water is considered acceptable for drinking (give an example from the Jordanian heritage), gardening and cleaning purposes.

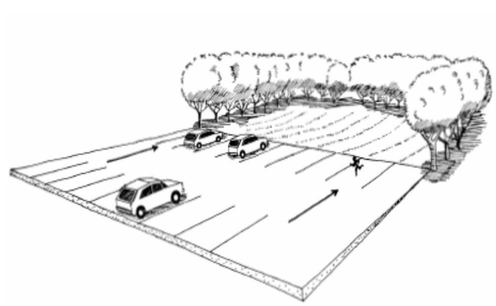
At an average rainy season, each single house rooftop in Jordan is able to collect about $10m^3$ of clean water. Just imagine that: if 50% of Jordanian house conduct such technique, what would be the amount of water collected? Do the simple math?

Micro-scale rainwater harvesting

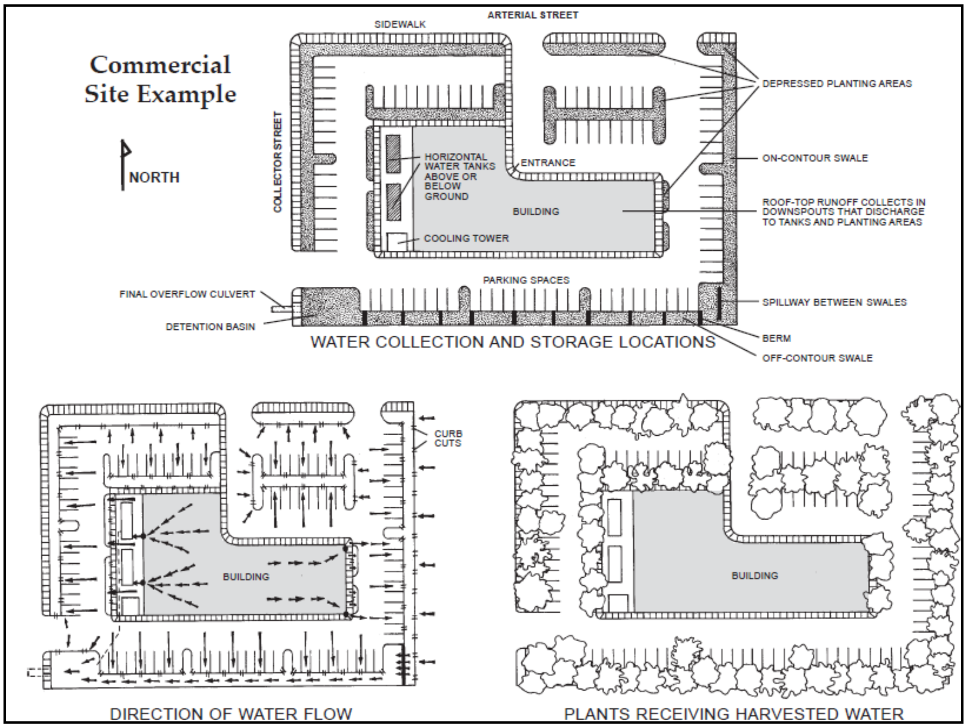
Example: micro-scale rainwater harvesting projects.



House rooftop

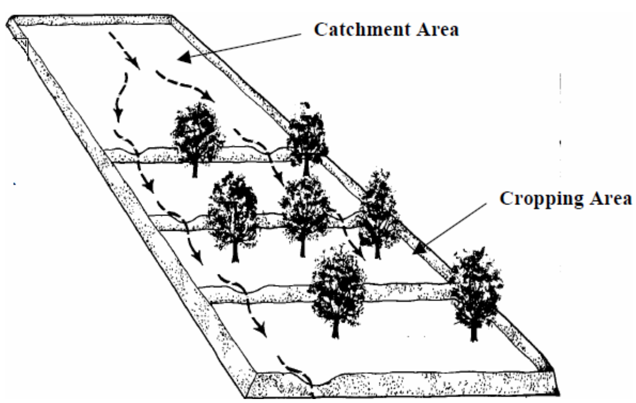


Parking lot



Micro-scale rainwater harvesting

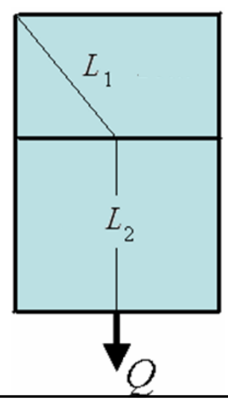
Example: micro-scale rainwater harvesting project (Cascade cropping area).



Micro-scale rainwater harvesting

Ex:

For the watershed shown in the previous example, estimate the maximum potential water volume that can be harvested from the storm given.



$C_1 = 0.8$, $A_1 = 40000\ m^2$

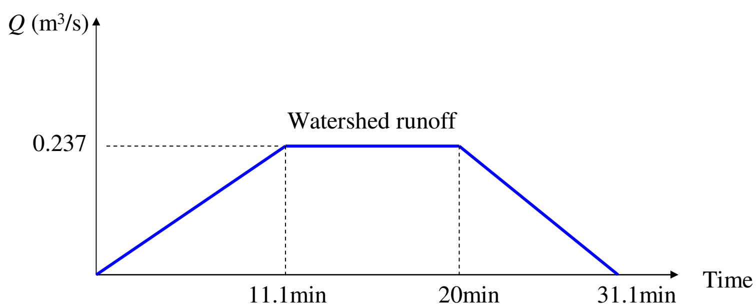
$S_1 = 1\%$, $n_1 = 0.025$, L_1=220m

$C_2 = 0.9$, $A_2 = 50000\ m^2$

$S_2 = 1.5\%$, $n_2 = 0.03$, L_2=250m

Micro-scale rainwater harvesting

Soln: given the hydrograph below.



The water volume possibly harvested from such watershed is the area under the runoff curve:

$V = Q \times$ time

$= 2\times(0.5\times11.1\times60\times0.237) + (20 - 11.1)\times60 \times0.237$

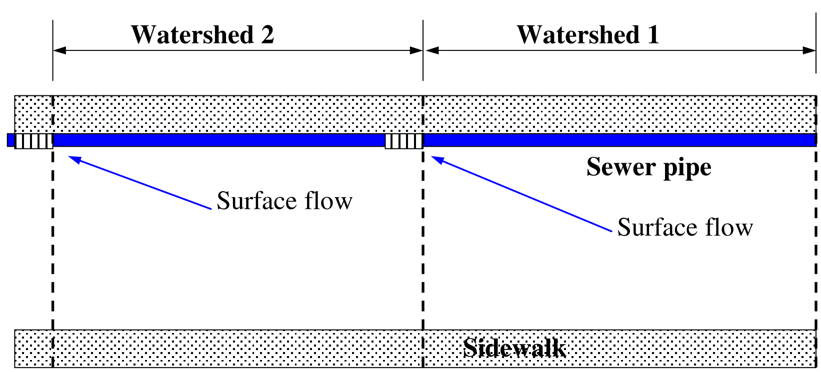
$= 284 m^3$

Design of storm sewer

Surface flow inlet: gutter.

Design of storm sewer

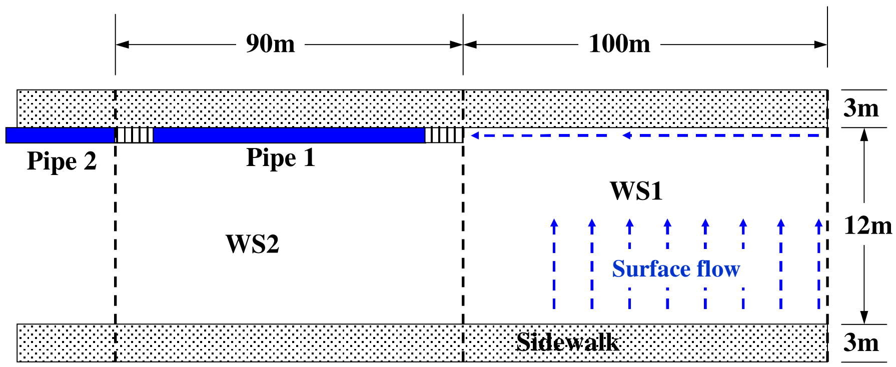
The gutter allows the surface runoff to inter the sewer pipe. After computing Q using the rational method, the pipe diameter (D) can be obtained as the best hydraulic section. The minimum distance between the gutters will not be detailed here.



Design of storm sewer

Ex:

Design concrete (n_c = 0.014) storm water drain pipes in street of 1% slope. Use street characteristics as C_s = 0.9 and n_s = 0.015. Use IDF curves given previously. Assume sidewalk as street. Use storm of 50 years return period, why????



Design of storm sewer

Flow in pipe 1 from WS1:

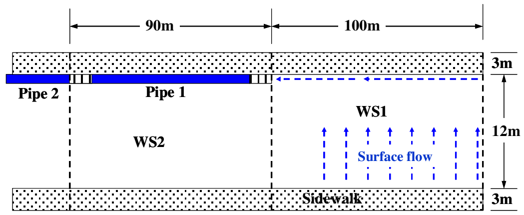
Surface flow longest path in WS1 is $L_1 = 3 + 12 + 100 = 115$m.

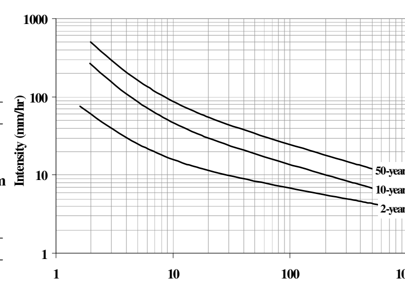
$tc_1 = 0.828\times(115\times0.015)^{0.467}/0.01^{0.235} = 3.15$ mins.

Use tc_1 = 3mins (sometimes t_c = minimum inlet time = 5mins)?

i = 300mm/hr, $A = 100 \times 18 = 1800\text{m}^2$

$Q_1 = 0.278 \times 0.9 \times 300 \times (1800/10^6) = 0.135\text{m}^3/\text{s}$





Design of storm sewer

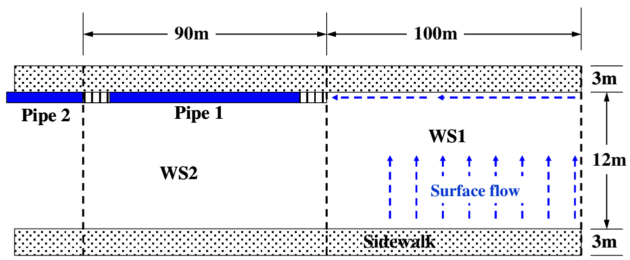
Pipe 1 diameter D_1 = ??

Use Manning $Q = 1/n \times A \times R^{2/3} \times S^{0.5}$

The best section of circular section:

$Q_1 = 0.135 m^3/s = (1/0.014) \times (0.77 D_1^2) \times (0.286 D_1)^{2/3} \times 0.01^{0.5}$

$D_1 = 0.34$m, use $D_1 = 0.35$m = 350mm.



Design of storm sewer

Flow in pipe 2 from WS1 + WS2:

Surface flow longest path in WS2 is $L_2 = 3 + 12 + 90 = 105$m.

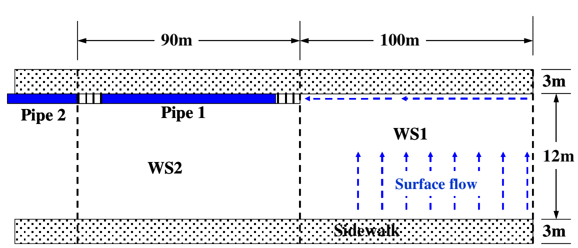
$tc_2 = 0.828 \times (105 \times 0.015)^{0.467} / 0.01^{0.235} = 3$ mins.

To pipe 2 inlet, the time of concentration is either:

tc_2 or (tc_1 + travel time in pipe 1), why ????.

In pipe 1, the travel time = L_1/V_1

Use the partial flow diagram to find V_1



Design of storm sewer

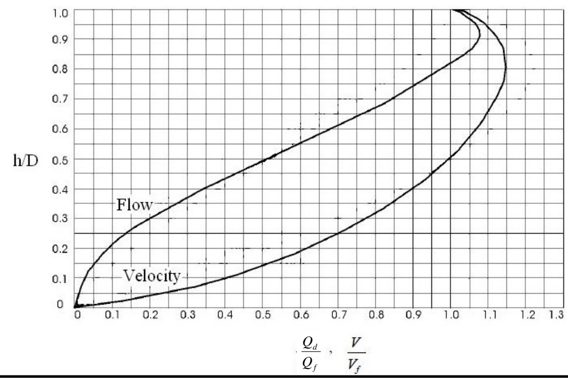
To find V_1 from the partial flow diagram, compute Q_1/Q_{full} = ??

$$Q_{full} = \frac{1}{n}\frac{\pi}{4}D^2\left(\frac{D}{4}\right)^{2/3}\sqrt{S_o} =$$

$$\frac{1}{0.014}\frac{\pi}{4}(0.35)^2\left(\frac{0.35}{4}\right)^{2/3}\sqrt{0.01} = 0.135\ m^3/s$$

➡ $Q_1/Q_{full} = 1$

➡ $V_1/V_{full} = 1.14$



Design of storm sewer

Find V_{full} from Manning as:

$$V_{full} = \frac{1}{n}\left(\frac{D}{4}\right)^{2/3}\sqrt{S_o} = \frac{1}{0.014}\left(\frac{0.35}{4}\right)^{2/3}\sqrt{0.01} = 1.41\ m/s$$

from $V_1/V_{full} = 1.14$ ➡ V_1 = 1.6m/s

therefore, tc_1 + travel time in pipe1=

tc = 3.15 + (100/1.6)/60 = 4.2 mins > tc_2

Design of storm sewer

For tc = 4.2 mins, i = 200mm/hr, A = 1800 + 90 × 18 = 3420m^2

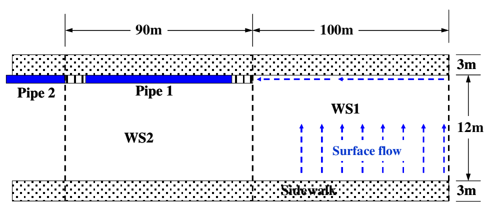
$Q_2 = 0.278 \times 0.9 \times 200 \times (3420/10^6) = 0.17\text{m}^3/\text{s}$

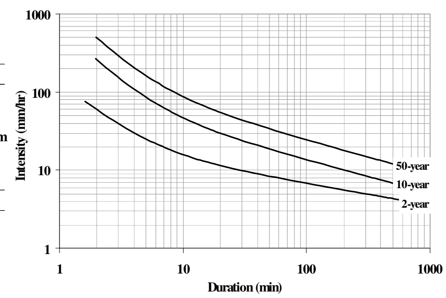
Pipe 2 diameter D_2 = ??

Use the best section $Q = 1/n \times A \times R^{2/3} \times S^{0.5}$

$Q_2 = 0.17\text{m}^3/\text{s} = (1/0.014) \times (0.77D_2^2) \times (0.286D_2)^{2/3} \times 0.01^{0.5}$

D_2 = 0.37m, use D_2 = 0.4m = 400mm.





Engineering Hydrology

110401454

Measuring flow from large-scale watersheds

Instructor: Dr. Zeyad Tarawneh

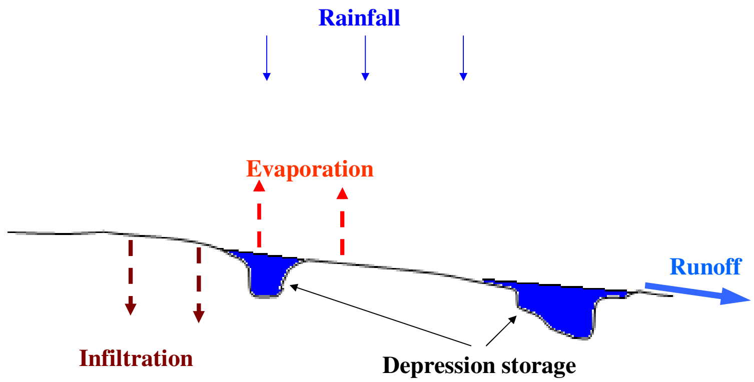
Macro-scale watersheds: measuring the flow

The estimation of the surface runoff generated from large watersheds (Macro-scale) depends on estimating the losses from the total precipitation. Such losses are: the evaporation, the soil infiltration, the surface storage and the interception (depends on the vegetation cover).

After abstracting (deducting) losses from the total precipitation, the net rain (**excess rain**) will run on the land surface forming the surface runoff.

The task is to compute the excess (net) rainfall after deducting the losses from the total precipitation.

Hydrologic parameters



Hydrologic parameters: precipitation

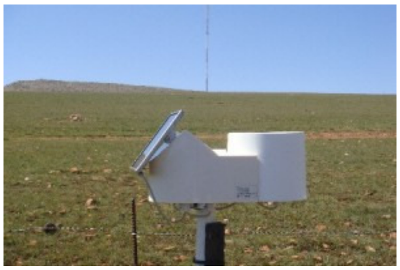
It is considered as the primary input variable in the hydrologic cycle. Precipitation occurs as: rain, snow or hail.

Precipitation is derived mainly from the atmospheric water, therefore its form (rain, snow,..) and quantity are being influenced by climatic variables like wind, temperature and atmospheric pressure.

Precipitation is a random variable having spatial and temporal (time) variability.

Measuring the precipitation

Precipitation is measured in gauging stations. The unit to measure precipitation is mm depth.

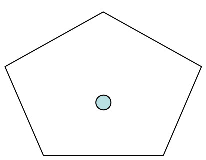


Automated rainfall gauge

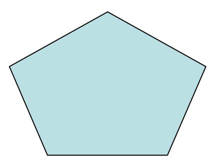
Traditional rainfall gauge

Estimation of the precipitation

Precipitation at un-gauged site (location without gauging station) can be estimated as point or areal perspective.



Point estimation



Areal estimation

The point estimation of precipitation can be made using the weighted average distance method developed by the National Weather Service. Given precipitation at gauged sites and the distances between the gauged sites and un-gauged site, the precipitation at the un-gauged site can be obtained.

Estimating the precipitation

The point estimation of the un-gauged site precipitation is:

$$P_{un-gauged} = \frac{\sum P \times W}{\sum W}$$

Where

P: the gauged site precipitation

W: the gauged site weighted distance, $W = 1/D^2$,

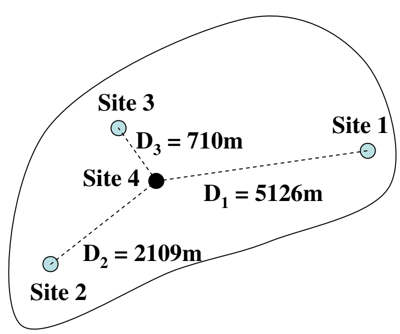
D: distance between the gauged and un-gauged site

Estimating the precipitation

Ex:

Estimate the rainfall at the un-gauged site # 4 based on the rainfall at the neighboring gauged sites.

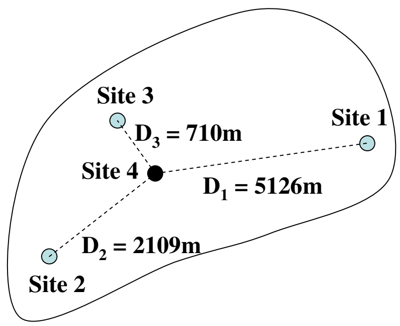
Site	rainfall (mm)
1	14
2	21
3	11



Estimating the precipitation

Soln:

Site	rainfall (mm)	D (km)	W	$P \times W$
1	14	5.126	0.038	0.533
2	21	2.109	0.225	4.721
3	11	0.710	1.984	21.821
		$\sum W =$	2.247	$\sum W \times P$ =27.075



$$P_{site4} = \frac{\sum P \times W}{\sum W}$$

$$P_{site4} = \frac{27.075}{2.247} = 12.05mm$$

Estimating the precipitation

The average precipitation over the watershed is an important hydrologic parameter. The areal (average) precipitation can be found using the Thiessen polygon method:

$$\overline{P} = \frac{\sum P \times A}{\sum A}$$

Where

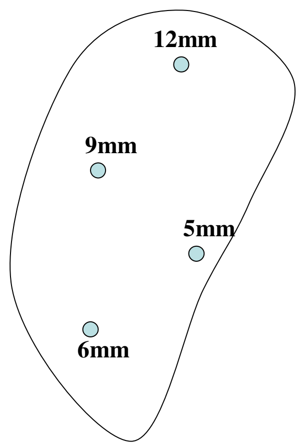
P: the precipitation in the thiessen polygon

A: area formed by thiessen polygons.

Estimating the precipitation

Ex:

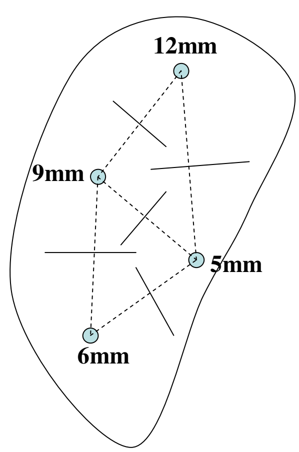
Estimate the areal rainfall for the following watershed.



Estimating the precipitation

Soln:

Connect the sites and bisect the distance between sites.



Estimating the precipitation

Soln:

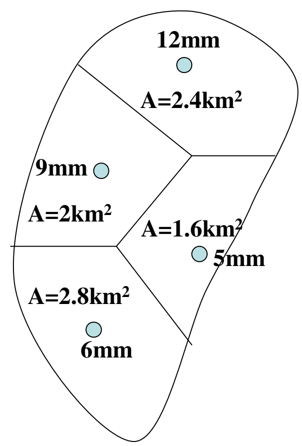
Calculate the area entrapped by each polygon.

Assume area are calculated as shown below.

A	$P \times A$
2.4	28.8
2.0	18.0
1.6	8.0
2.8	16.8

$\sum A = 8.8 \quad \sum P \times A = 71.6$

$$\overline{P} = \frac{\sum P \times A}{\sum A} = 8.14 mm$$



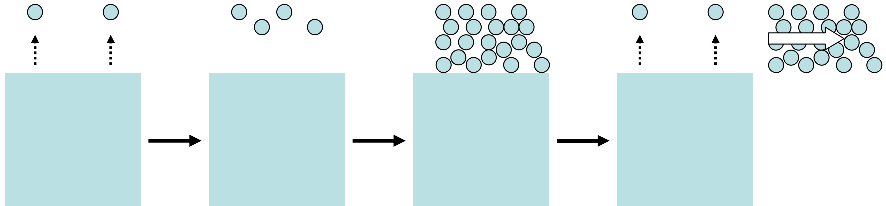
Hydrologic parameters: evaporation

The net rain (excess) that generates surface runoff is that part of the total precipitation after deducting the evaporated, the intercepted, the infiltrated and the precipitation that is stored in depressions (small holes in the surface).

The evaporated precipitation depends on many factors like the temperature, wind speed, relative humidity, soil condition, and type of vegetation cover, therefore it the most difficult parameter to estimate. The evaporation is usually measured experimentally using evaporation pans. The units of the evaporation is (mm/hr).

Hydrologic parameters: evaporation

Wind effect



If the air surrounding the land or water body becomes fully (highly) saturated, the potential evaporation decreases. The wind moves the evaporated particles away leaving the space empty to new evaporated particles (wind increase evaporation).

Estimating the evaporation

The evaporated precipitation can be estimated using the energy balance method adjusted for the soil and the vegetation cover. It is humble method, why??:

$$E_r(m/s) = \frac{R_n}{l_v \rho} \times k_s \times k_c$$

Where

R_n: net solar radiation (W/m^2),

ρ: water density (1000kg/m^3),

l_v: latent heat of vaporization (J/kg),

k_s: soil coefficient, usually k_s = 1 for complete wet soil,

k_c: vegetation cover coefficient, usually k_c = 1 in arid regions.

In units (KJ/kg), the latent heat is $l_v = 2500 - 2.36\,T$

T: temperature (°C)

Estimating the evaporation

Ex:

Calculate the evaporation rate under net solar radiation of 200 W/m^2 and air temperature of 25 °C. Assume completely wet soil (k_s = 1) in arid region (k_c = 1).

Soln:

$l_v = 2500 - 2.36\,T = 2500 - 2.36\,(25) = 2441$ KJ/kg

$$E_r = \frac{R_n}{l_v \rho} \times k_s \times k_c = \frac{200}{2441000 \times 1000} \times 1 \times 1 =$$

$= 8.22 \times 10^{-8}$ m/s

= 7.1 mm/day

Hydrologic parameters: interception

The intercepted water is the part of precipitation that is intercepted by plant leaves. Therefore the leave size and the intensity of leaves highly affect the amount of water intercepted that will evaporate eventually and hence reducing the runoff.

The interception can be measured experimentally in the lab. In arid regions like Jordan, the plant cover is small while the evaporation rate is high, therefore the intercepted water can be neglected compared to the evaporated.

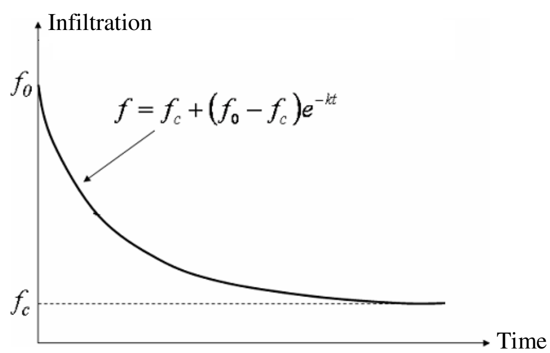
Hydrologic parameters: infiltration

The infiltrated precipitation depends on the soil type, rainfall intensity, surface conditions, and the vegetation cover. Horton suggested the following model to estimate the infiltration rate of water:

$$f = f_c + (f_0 - f_c)e^{-kt}$$

f : infiltration rate (mm/hr)
f_c : equilibrium infiltration capacity (mm/hr)
f_0 : initial infiltration capacity (mm/hr)
k : infiltration constant / hr
t : time (hrs)

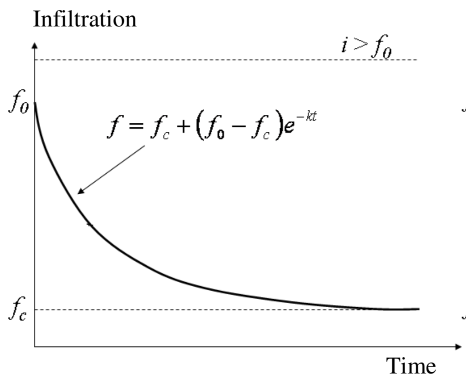
Hydrologic parameters



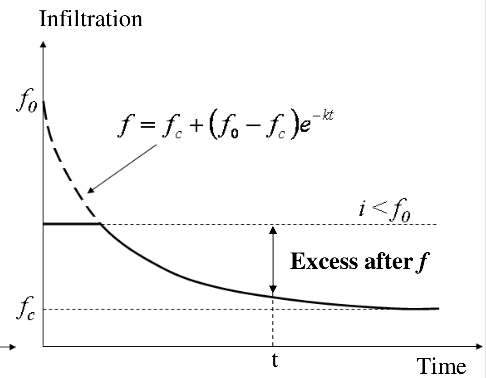
At time t = 0, the infiltration begins with its the initial infiltration rate f_0, however as time proceeds the infiltration rate decreases to reach its equilibrium infiltration f_c.

Hydrologic parameters

Understand the following cases:



Case1:
Precipitation (i) > initial infiltration



Case2:
Precipitation (i) < initial infiltration

Hydrologic parameters: depression storage

The precipitation stored in depressions is that part stored in small holes in land surface. It will eventually evaporate. Depression storage highly affects the runoff from storms of short duration with low precipitation intensity. The depression storage is:

$$V_S = S_c\left(1 - e^{-P_n/S_c}\right)$$

V_S: water stored (mm/hr)
S_c: total storage capacity (mm/hr)
P_n: net rainfall for storage (mm/hr)
P_n = total rainfall – evaporation – interception – infiltration

Hydrologic parameters

Ex:

A 2hrs rainfall storm with pattern as shown below. Given the soil equilibrium infiltration capacity of 0.75mm/hr, an initial infiltration of 5mm/hr, and the infiltration constant is 0.29, what is the net rain available for runoff assuming that depression storage is for the first hour with total storage capacity of 2mm/hr. Assume completely wet soil in arid region under air temperature of 10°C and solar radiation of 150W/m^2. Neglect interception losses.

Hour	Total rainfall intensity (mm/hr)
1	10.3
2	12.5

Hydrologic parameters

Soln: $l_v = 2500 - 2.36\,T = 2500 - 2.36\,(10) = 2476.4$ KJ/kg

$E_r = 150/(2476400\times1000) = 0.22$mm/hr

For the first hour, the infiltrated water is:

$$f = 0.75 + [5 - 0.75]e^{-0.29\times1} = 3.93\text{mm/hr}$$

The net rain for storage P_n =

= precipitation – evaporation – interception – infiltration

= 10.3 – 0.22 – 0 – 3.93 = 6.15mm/hr

The depression storage:

$$V_S = 2\,[1 - e^{(-\,6.15/2)}] = 1.9\text{mm/hr}$$

The net rain available for runoff = 10.3 – 0.22 – 3.93 – 1.9

= 4.25mm/hr

Hydrologic parameters

The following table shows the results over the 2 hours storm.

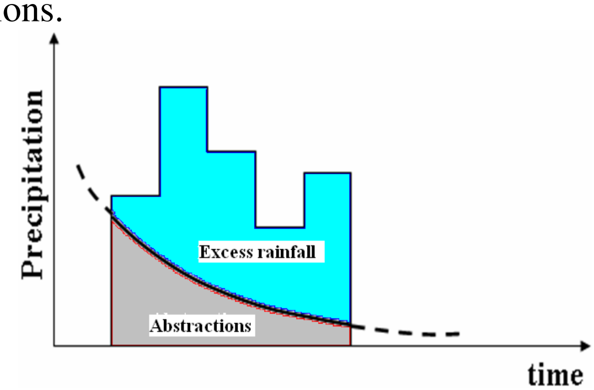
Hour	Gross rainfall intensity (mm/hr)	E_r (mm/hr)	f (mm/hr)	P_n (mm/hr)	V_S (mm/hr)	Net rain (mm/hr)
1	10.3	0.22	3.93	6.15	1.92	4.25
2	12.5	0.22	3.13	9.15	0	9.15

Note that storage = 0 for the 2nd hour

Hydrologic parameters

SCS method for deducting abstractions:

The Soil Conservation Services (SCS) developed a method to calculate the excess rain available for runoff. Excess rain is the total rain after deducting all abstractions.



Hydrologic parameters

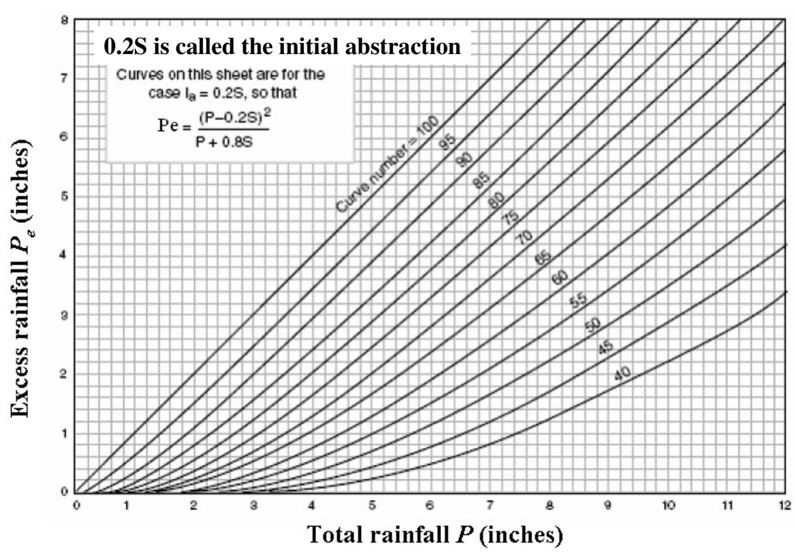
The SCS developed the method to calculate the excess rain for nearly flat watersheds (slope ≤ 5%). What will be the case for watersheds of slope > 5%? Think about it?.

The method considers the watershed soil type, land cover, and the antecedent moisture condition (AMC) based on the 5-day antecedent rainfall.

Based on huge number of observations, the SCS method resulted in many curves that relate the excess rain available for the direct runoff versus the total rainfall when the antecedent moisture condition is average (AMC II). For moisture conditions rather than the average a slight modification is needed.

Hydrologic parameters

SCS curve number for soils (AMC II).



Hydrologic parameters

The SCS classified the antecedent moisture condition (AMC) as follows: AMC I for dry soil, AMC II for soil with average moisture, and AMC III for wet soil.

The SCS classified the soil as follows:

Group A: Deep sands, silts

Group B: Sandy loam

Group C: Clay loam, shallow sandy loam

Group D: Soils that swell significantly, plastic clays.

Hydrologic parameters

The SCS method supplies a Curve Number (CN) according to the land cover and soil group based on AMC II condition. For example refer to the table below.

Land use	Hydrologic soil group			
	A	B	C	D
Cultivated lands	72	81	88	91
Range lands	39	61	74	80
Forest land	45	66	77	83
Desert land	63	77	85	88

Hydrologic parameters

Having the CN determined for the watershed, then the maximum retention storage S (max rain can be stored) in inches is:

$$S = \frac{1000}{CN} - 10$$

The excess rain (**in inches**) for the direct runoff is:

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

$0.2S$ is called the initial abstraction. $P_e = 0$ for $P < 0.2S$

Hydrologic parameters

SCS method for abstractions:

Given the CN at AMC II, the equivalent CN at AMC I and at AMC III is found as:

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

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

Hydrologic parameters

Ex:

Determine the excess rain of the 3 inches total rain on nearly flat clay loam watershed of $18km^2$ under dry soil condition. Among the $18km^2$, $7km^2$ is range land, while the rest is cultivated land.

Soln:

AMC for the whole watershed is AMC I,

Hydrologic soil group is C,

The CN of the $7km^2$ part = 74,

The CN of the $11km^2$ part = 88,

The weighted average CN = (7×74 + 11×88)/18 = 82.5

Hydrologic parameters

Soln:

The average CN = 82.5 is based on moisture condition of the AMC II type. The CN(I) for the AMC I is:

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)} = \frac{4.2 \times 82.5}{10 - 0.058 \times 82.5} = 66.5$$

The max potential retention S is:

$$S = \frac{1000}{CN} - 10 = \frac{1000}{66.5} - 10 = 5.03\,inches$$

The excess rainfall for the direct runoff is:

$$P_e = \frac{(P - 0.2S)^2}{(P + 0.8S)} = \frac{(3 - 0.2 \times 5.03)^2}{(3 + 0.8 \times 5.03)} = 0.56\,inches$$

Engineering Hydrology

110401454

Macro-scale basin: computing the runoff

Instructor: Dr. Zeyad Tarawneh

Computing the surface runoff

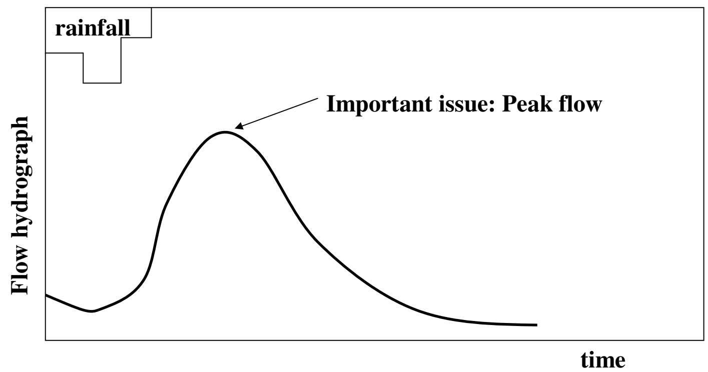
In this part, our task is to compute the surface runoff (surface flow) resulted from a rainfall event on a watershed regardless of its size (large or small).

The surface runoff is the actual response of the watershed to the cause (rainfall event). Some watersheds discharge large peak flow in short time, while others discharge low peak flow after long time. Such behavior is affected by the watershed area, slope, surface roughness and vegetation cover. It should be noted that the rainfall pattern also affects the flow pattern as well. The watershed response (flow) over the time is called the Hydrograph.

Hydrograph

It is a graphical presentation that describes how the watershed flow develops over the time from the beginning of the rainfall and thereafter.

The following plot shows a typical hydrograph.



Hydrograph

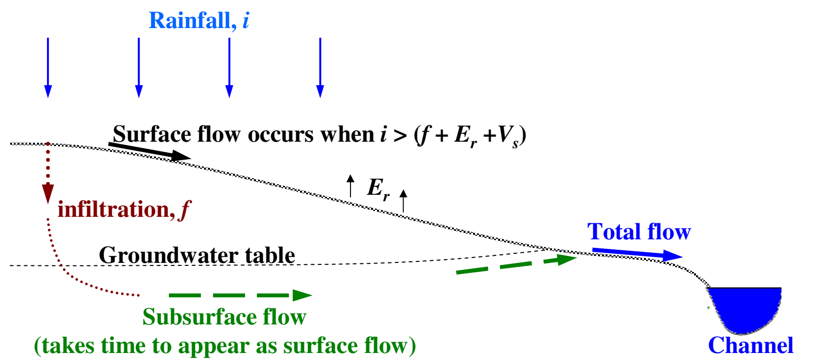
The total flow hydrograph could be result of two flows:

1- Subsurface flow (base flow) due to groundwater. It depends on past rainfall events and the underground forming layers (material of ground layers).

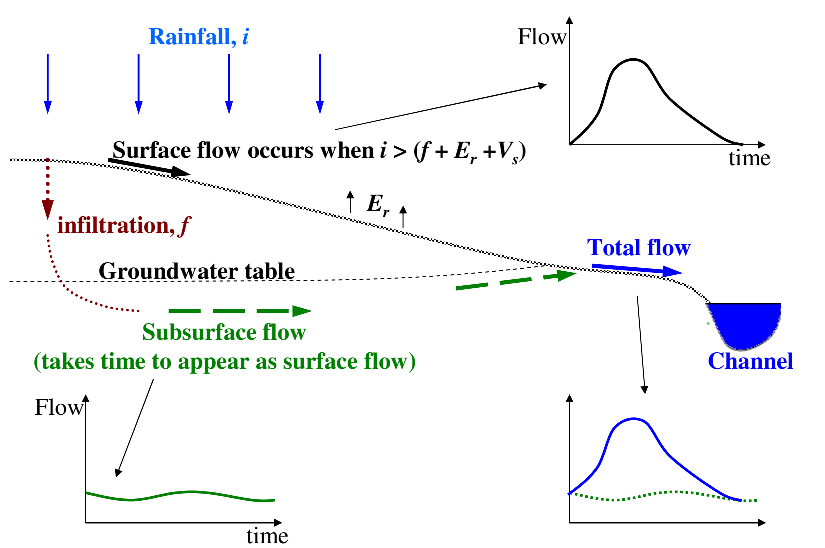
2- Surface runoff (called Hortonian overland flow or direct runoff). It depends on many factors like the rainfall duration and intensity (i and d), the evaporation (E_r), the infiltration (f), depression storage (V_s).

Hydrograph

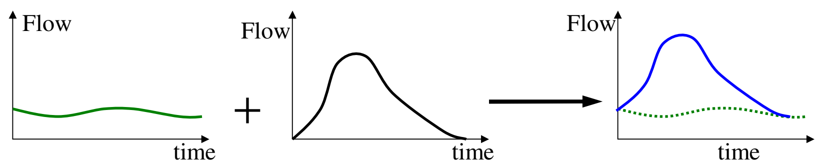
The following schematic plot defines the surface flow (Hortonian overland flow) and the subsurface flow.



Hydrograph



Hydrograph



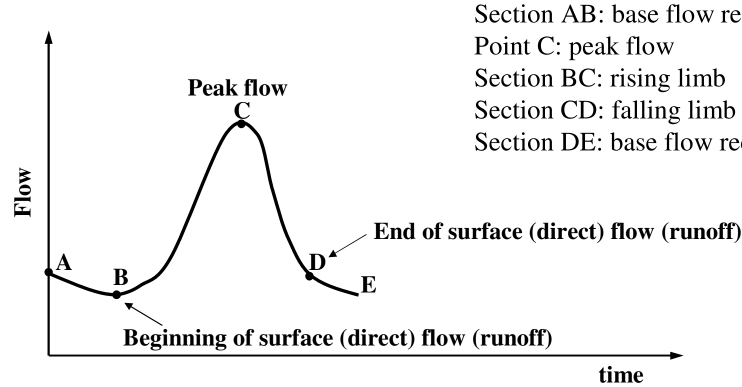
Subsurface flow + **Surface flow** ⟶ **Total flow**

Both of the total flow and subsurface can be measured using Weirs. To obtain the surface flow, then:
Surface flow = Total flow - subsurface flow

Hydrograph components

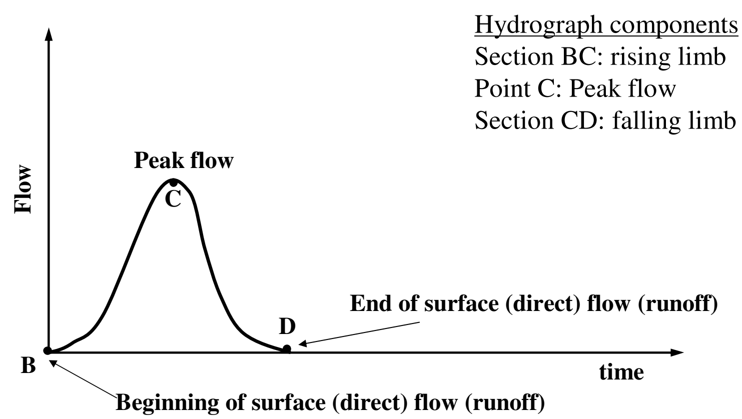
Component of total flow hydrograph from a watershed.

<u>Hydrograph components</u>
Section AB: base flow recession
Point C: peak flow
Section BC: rising limb
Section CD: falling limb
Section DE: base flow recession



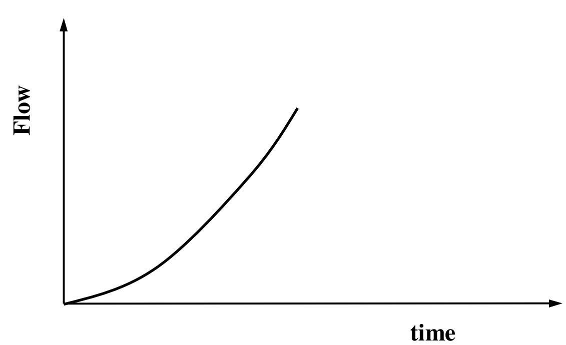
Hydrograph components

Component of surface flow hydrograph from a watershed.



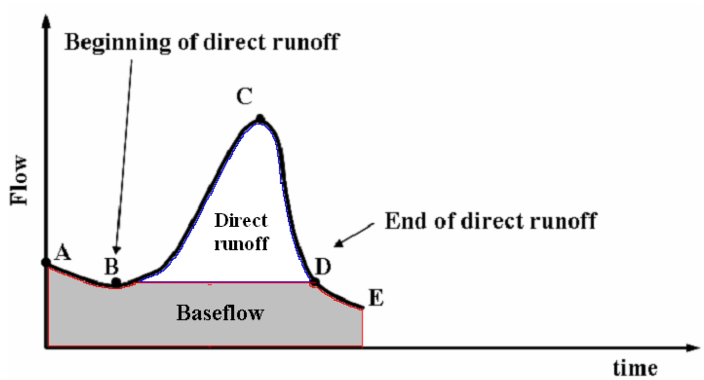
Hydrograph components

Is this a hydrograph? Why??



Base flow separation

When the hydrograph consists of sub-surface (base flow) and surface flows (direct runoff), then to estimate the surface flow from a rainfall event, the base flow must be subtracted (separated) from the total flow.



Base flow separation

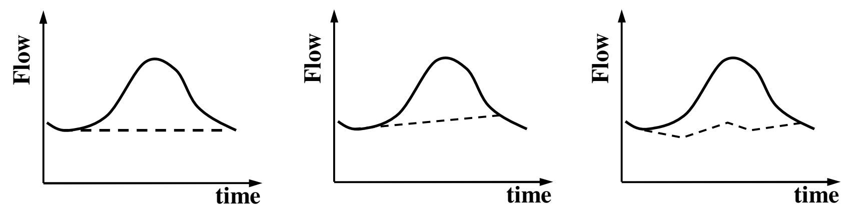
To estimate the direct runoff (surface runoff) as the watershed response to the cause (rainfall), then the base flow must be separated (extracted):

Surface runoff = total runoff - base flow

In literature, there are several methods to separate the baseflow (to estimate its quantity). Among these are: the straight horizontal line method, the fixed base method, and the variable slope method. The straight horizontal line method will be adopted to separate the base flow from the total runoff.

Base flow separation

The three methods:



Straight horizontal line method

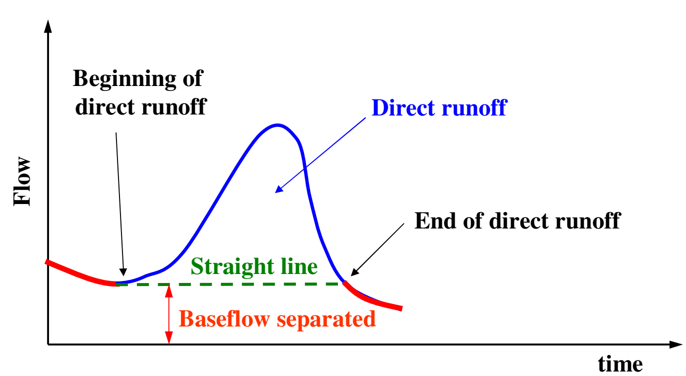
Fixed base method

Variable slope method

In reality: how can you know the base flow pattern?

Base flow separation

The straight horizontal line method: to separate the baseflow, construct a straight horizontal line at the beginning of the rising limb of the hydrograph.



Direct runoff computation

Ex:

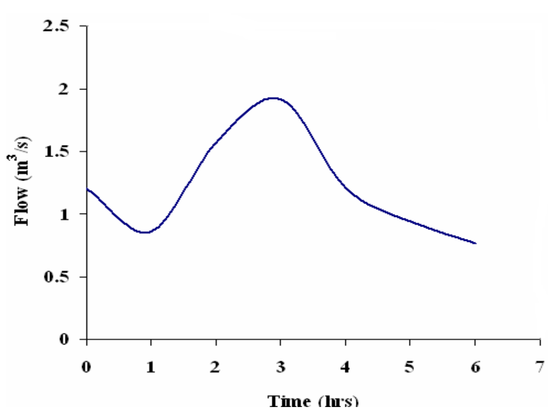
A large watershed discharges runoff to its outlet. The measured total runoff is shown in the table below. Estimate the direct runoff (surface runoff)?

Time (hr)	Total Runoff (m^3/s)
0	1.2
1	0.86
2	1.57
3	1.92
4	1.21
5	0.94
6	0.77

Direct runoff computation

Soln:

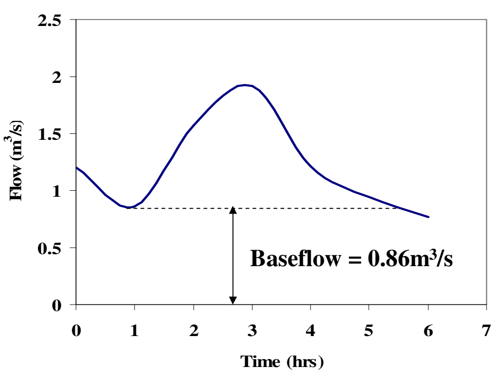
The following plot shows the hydrograph of the watershed total runoff. Observe the base flow recession portion and the rising limb. The baseflow will be at first separated using the straight line method.



Direct runoff computation

Soln:

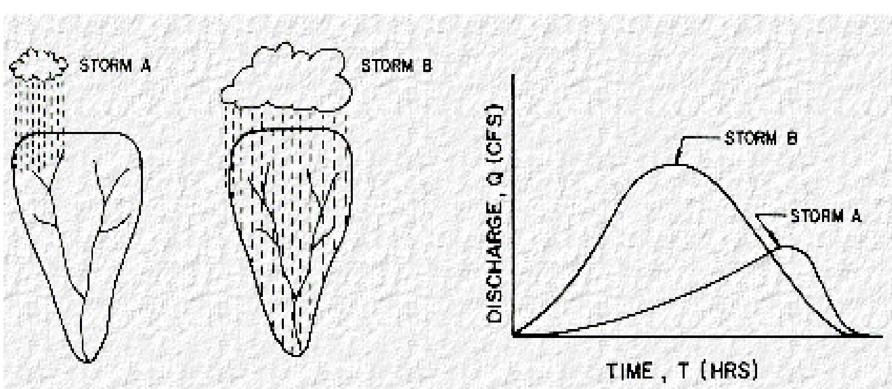
The direct runoff can be obtained after separating (subtracting) the baseflow from the total runoff. The direct runoff is the watershed response that will be used to derive the Unit Hydrograph.



Time	Total runoff	Baseflow	Direct runoff
0	1.2	1.2	0
1	0.86	0.86	0
2	1.57	0.86	0.71
3	1.92	0.86	1.06
4	1.21	0.86	0.35
5	0.94	0.86	0.08
6	0.77	0.77	0

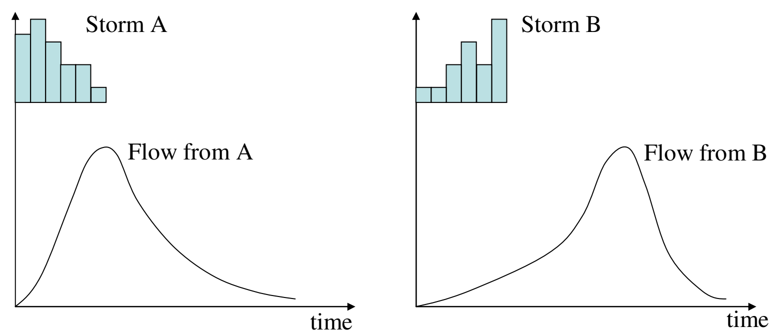
Hydrograph pattern

Explain the following hydrographs resulted from storms A and B, i.e. observe the effect of storm size.



Hydrograph pattern

Explain the following hydrographs resulted from storms A and B, i.e. observe the effect of storm shape.



Computing the surface runoff

The peak surface flow from small watersheds (< $3km^2$) can be computed using the rational method, that can not be used to compute the flow from large watersheds.

The challenge is: how to compute the surface runoff that the watershed will discharge from a given rainfall storm (storm is known)?

The answer: you either wait next to the weir and measure the runoff (think about the cost and time!!!!!!), or you may understand, derive and use the watershed response function to compute the flow. The watershed response function is called the Unit Hydrograph (UH).

Unit Hydrograph (UH) idea

For large watersheds, the resulted flow and peak flow can be computed using the Unit Hydrograph (UH) principle. The UH is the function that describes how would the watershed respond to certain rainfall event.

Unit of what? Unit of the cause (1cm of the effective rainfall = excess rainfall).

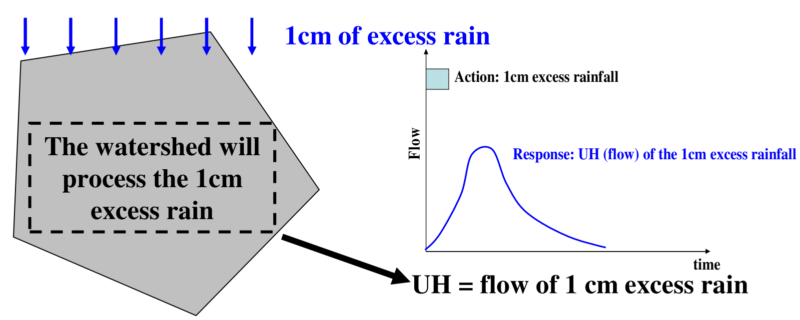
Why unit of the excess rainfall? The unit is 1 (one) and the value one will not affect the results if you multiply or divide by it. Recall the unit vector idea in the course Statics.

UH idea

Idea: imagine that you release the 1cm of excess rain on the watershed. The resulted flow is the UH.

What happened? The watershed processes the 1cm excess rain and translates it as flow values over the time.

Therefore, each watershed has its own UH (its own response to the 1cm excess rain).



UH idea

If the duration of the 1cm excess rainfall is X hrs, then the produced flow (UH) is called the X-hr UH. For example: 1-hr UH, 2-hr UH, and so on.

For computation ease, the 1-hr UH will be adopted, why???

Assumptions:

1. The excess rainfall has constant intensity,
2. The excess rainfall is distributed uniformly over the entire watershed.
3. The watershed characteristics remain the same.

UH usefulness

How to derive the UH for a watershed?

UH can be derived given the actual rainfall data (P) and the actual flow data (Q) from gauging stations. In that case:

$$UH = Q / P \qquad (m^3/s/cm)$$

Why to derive the UH?
If the watershed UH is available, then the flow (Q) resulted from the rainfall pulse (P) over the watershed can be computed easily (no need to wait next to the weir) using the general equation:

$$Q = P \times UH$$

UH values

Ex:

Assume that someone derived the 1-hr UH for a watershed as follows:

Time (hr)	0	1	2	3	4
UH value ($m^3/s/cm$)	0	1.3	2.1	0.9	0

1- Explain the $1.3m^3/s/cm$ at the time t = 1hr?

2- What is the value of the rain caused the UH flow?

3- How long the watershed discharges flow?

4- Why at the time t = 0, the UH value is 0?

5- What is the UH value at time t = 1.5hrs?

UH values

Answers:

The $1.3m^3/s/cm$ is the flow value the watershed discharges at the time t = 1hr from the 1cm excess rain.

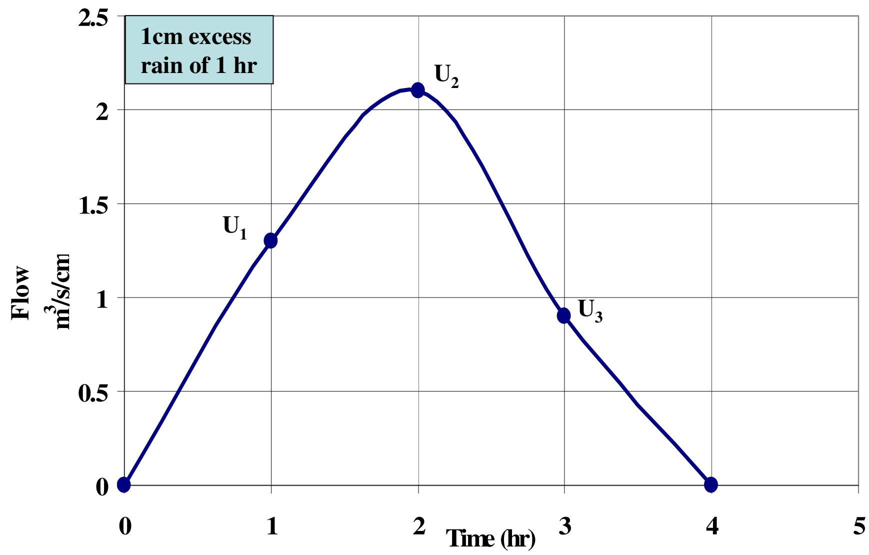
The rainfall value that caused the UH flow is 1cm.

The watershed discharges measurable flow over 3 hrs.

At the time t = 0, the UH value is 0, because the rain (cause) just begins, therefore, the watershed response is 0.

At time t = 1.5hrs, UH value can not be derived at the 1-hr scale, no need for it. Linear interpolation is not OK.

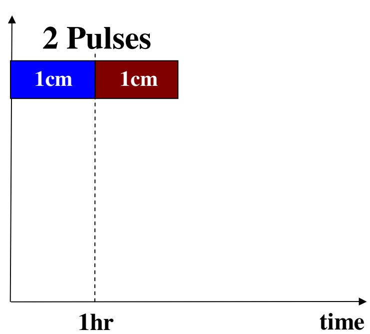
UH values



UH: multi-pulses

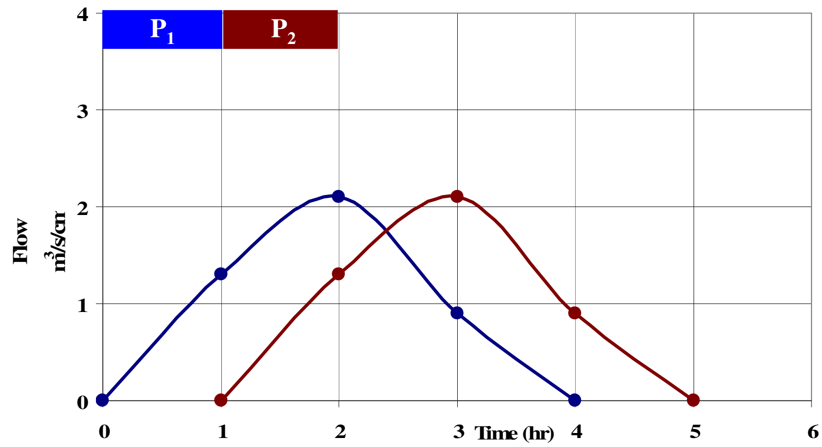
Ex:

Assume the same watershed is subjected to 2 successive storms (pulses) each of 1hr duration and 1cm excess rain as shown, compute the net flow from the two storms? Each pulse causes UH as shown (table)



Time (hr)	0	1	2	3	4
UH value ($m^3/s/cm$)	0	1.3	2.1	0.9	0

UH: multi-pulses



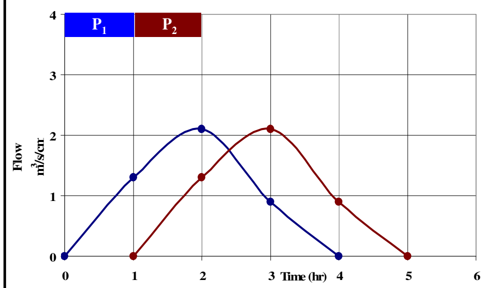
Question: compute the net flow at time t = 1 and 2hrs?
At t = 1hr, Q = 1.3m^3/s/cm, at t = 2hrs, Q = 2.1 + 1.3 = 3.4m^3/s/cm

UH: multi-pulses

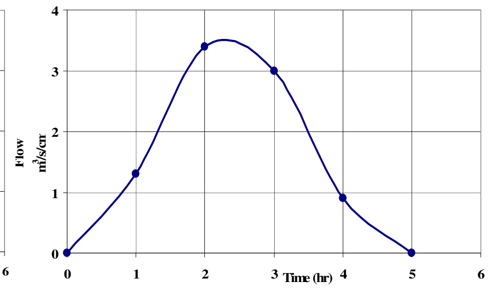
Table of calculations

Time (hr)	Flow from P_1 m^3/s/cm	Flow from P_2 m^3/s/cm	Net flow m^3/s/cm
0	0	0	0
1	1.3	0	1.3
2	2.1	1.3	3.4
3	0.9	2.1	3
4	0	0.9	0.9
5	0	0	0

UH: multi-pulses



2 Pulses separate flow



Net flow

Observe that the flow at time t = 2 is $Q_2 = P_1 \times U_2 + P_2 \times U_1$

UH formulation

Given the UH and the excess rainfall (P_m), the resulted direct runoff at time n (Q_n) from the watershed is computed as follows:

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1}$$

where

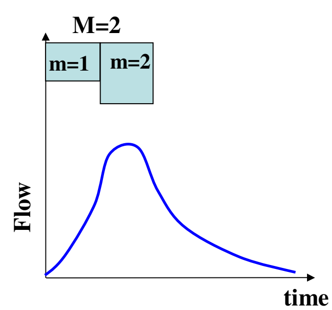
n: runoff time step (usually hr)

M: total # of rainfall pulses

m: rainfall pulse #

U_{n-m+1}: is the UH value

at time $n - m + 1$.



UH formulation

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1}$$

The runoff equation above can be re-written as follows:

$$Q_n = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + ... + P_n U_1$$

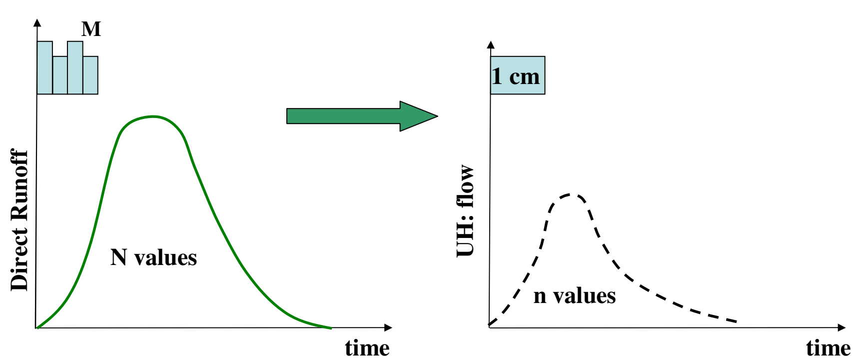
Question:

Assume storm of 2 pulses (P_1 and P_2), write the equation above?

Deriving the 1-hr UH values

Given N hrs actual surface runoff due to M hrs excess rainfall pulses, then the watershed will discharge flow from 1cm excess rain (UH) for n hrs.

$n = N - M + 1$.



Deriving the 1-hr UH

$$Q_n = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + ... + P_n U_1$$

From the equation above it can be seen that:

at n = 1, $Q_1 = P_1 U_1 \Longrightarrow U_1 = \frac{Q_1}{P_1}$

at n = 2, $Q_2 = P_1 U_2 + P_2 U_1 \Longrightarrow U_2 = \frac{Q_2 - P_2 U_1}{P_1}$

and so on……

Deriving the UH

Ex:

Watershed of 6.23 km^2 area discharges flow from 2-hr storm with excess rainfall as shown in the table. Derive the 1-hr UH.

Time (hr)	Excess rainfall (mm)	Direct runoff (m^3/s)
1	20	2.3
2	15	12.1
3		26.7
4		17.2
5		2.3

Deriving the UH

Soln:

From the table, $N = 5$, $M = 2$, then $n = N - M + 1$, so $n = 4$.

$$Q_n = \sum_{m=1}^{n\leq M} P_m U_{n-m+1} = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + \ldots + P_n U_1$$

for $n = 1$, $Q_1 = \sum_{m=1}^{1} P_m U_{1-m+1} = P_1 U_1$

for $n = 2$, $Q_2 = \sum_{m=1}^{2} P_m U_{2-m+1} = P_1 U_2 + P_2 U_1$

for n = 3, $Q_3 = \sum_{m=1}^{2} P_m U_{3-m+1} = P_1 U_3 + P_2 U_2$ and so on ….

Deriving the UH

Soln:

Results are shown below.

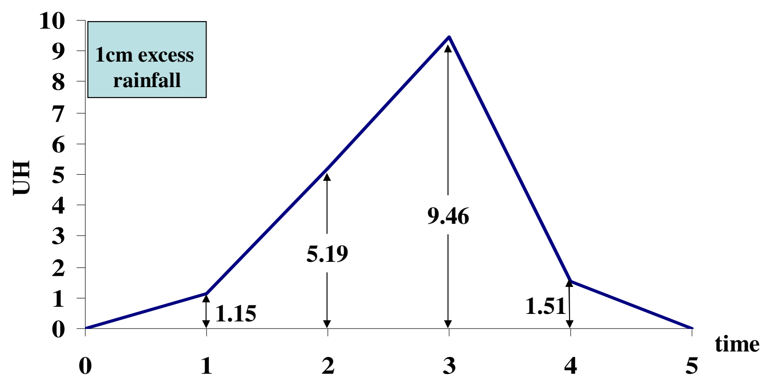
Time (hr)	Excess rainfall (cm)	Direct runoff (m^3/s)	Equation	UH ($m^3/s/cm$)
1	$P_1 = 2.0$	$Q_1 = 2.3$	$Q_1 = P_1 U_1$	$U_1 = 1.15$
2	$P_2 = 1.5$	$Q_2 = 12.1$	$Q_2 = P_1 U_2 + P_2 U_1$	$U_2 = 5.19$
3		$Q_3 = 26.7$	$Q_3 = P_1 U_3 + P_2 U_2$	$U_3 = 9.46$
4		$Q_4 = 17.2$	$Q_4 = P_1 U_4 + P_2 U_3$	$U_4 = 1.51$
5		$Q_5 = 2.3$		

Response to actual rain

Response to 1cm

Deriving the UH

Each 1-hr storm of 1cm excess rainfall will have the following UH.



Application on the UH

Ex:

For the watershed of 6.23 km^2 area and given the UH from the previous example, obtain the direct runoff hydrograph and find the peak runoff from 3 hrs storm of excess rainfall as shown below.

Time (hr)	Excess rainfall (mm)
1	8
2	10
3	5

Application on the UH

Soln:

Given the UH derived in the previous example, the runoff amount of the 3-hr storm can be obtained as follows:

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1} \quad = P_1 U_n + P_2 U_{n-1} + P_3 U_{n-2} + \dots + P_n U_1$$

at $n = 1$, $\quad Q_1 = \sum_{m=1}^{1} P_m U_{1-m+1} = P_1 U_1 \ = 0.8\times1.15 = 0.92\text{m}^3/\text{s}$

at $n = 2$, $\quad Q_2 = \sum_{m=1}^{2} P_m U_{2-m+1} = P_1 U_2 + P_2 U_1$

$= 0.8\times5.19 + 1\times1.15 = 5.3\text{m}^3/\text{s}.$

Application on the UH

at $n = 3$, $\quad Q_3 = \sum_{m=1}^{3} P_m U_{3-m+1} = P_1 U_3 + P_2 U_2 + P_3 U_1$

$= 0.8\times9.46 + 1\times5.19 + 0.5\times1.15 = 13.33\text{m}^3/\text{s}$

Why 3 ??

at $n = 4$, $\quad Q_4 = \sum_{m=1}^{3} P_m U_{4-m+1} = P_1 U_4 + P_2 U_3 + P_3 U_2$

$= 0.8\times1.51 + 1\times9.46 + 0.5\times5.19 = 13.26\text{m}^3/\text{s}.$

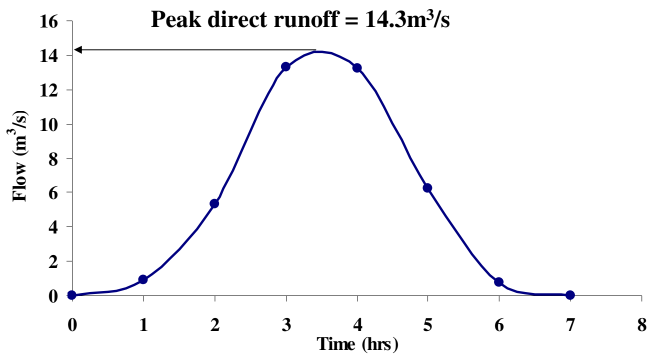
and so on……

Application on the UH

Result:

The watershed response as a runoff hydrograph due to the 3-hr storm.

Time (hrs)	Flow (m^3/s)
0	0
1	0.92
2	5.30
3	13.33
4	13.26
5	6.24
6	0.76
7	0



Review on the UH

Questions:

Two watersheds of the same area, soil type, surface roughness and vegetation cover but of different slopes, do they have the same UH?

Two watersheds of the same slope, soil type, surface roughness and vegetation cover but of different areas, do they have the same UH?

Why do we need to derive the UH for a watershed, and up to what watershed size the derivation of the UH is useful?

Computing the UH for ungauged WS

Synthetic Unit Hydrograph:

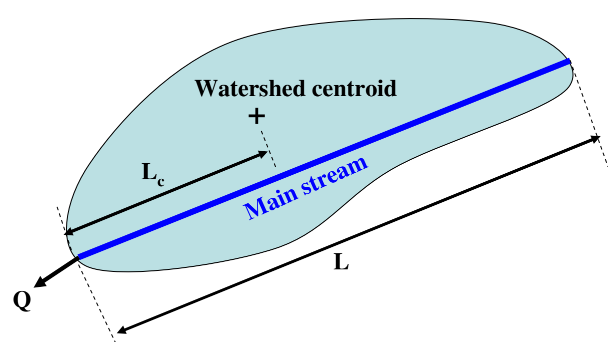
When the watershed equipped with gauging stations to measure the actual *Q* resulted from given excess rainfall *P*, then the UH can be derived as shown previously. However, most of watersheds may not have gauging stations, therefore synthetic hydrographs is used to estimate the peak discharge.

Based on huge field observations, Snyder developed a methodology to derive the Synthetic Unit Hydrograph based on the watershed characteristics like area, slope and distances along the main stream.

Measuring the surface runoff

Snyder's synthetic Unit Hydrograph:

To develop the Snyder's synthetic unit hydrograph, five inputs are required: watershed area (A), the length of the main stream from outlet to divide (L), the length to the centroid of the basin (L_c), and two coefficients (C_t and C_p).



Measuring the surface runoff

Snyder's synthetic Unit Hydrograph:

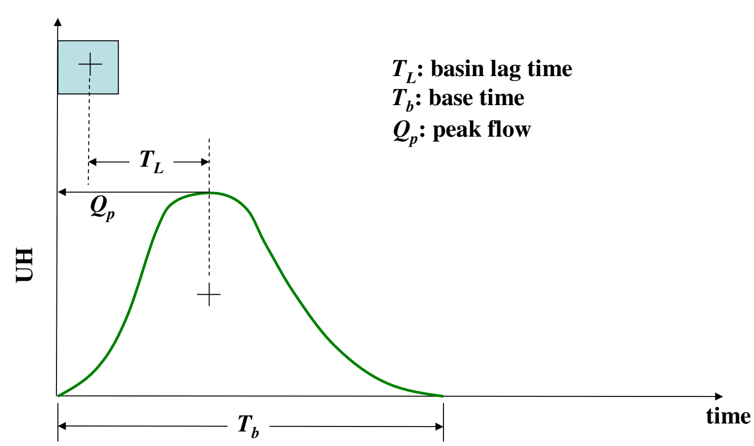
Snyder developed equations (models) to measure the flow time and peak flow based on ***observations*** and such models need corrections. The coefficients C_t and C_p are corrections for the time and the amount of peak flow.

Generally, typical values for C_t ranges from 0.3 – 6, while for C_p ranges from 0.31 – 0.93.

In practice: think how can you estimate C_t and C_p for a given watershed ??????

Measuring the surface runoff

Snyder's synthetic Unit Hydrograph: definitions.



Measuring the surface runoff

Procedures to derive the Snyder's UH:

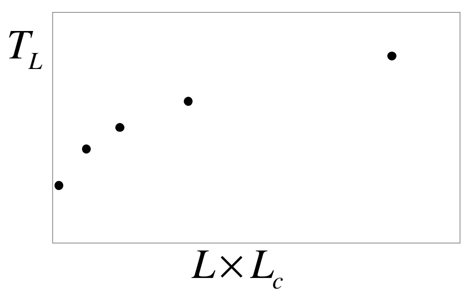
The basin lag: time difference between the centroid of the excess rainfall and the centroid of the hydrograph is:

$$T_L = 0.75 C_t \left(L \times L_c\right)^{0.3} \qquad T_L \text{ (hr)}, L \;\&\; L_c \text{ (km)}$$

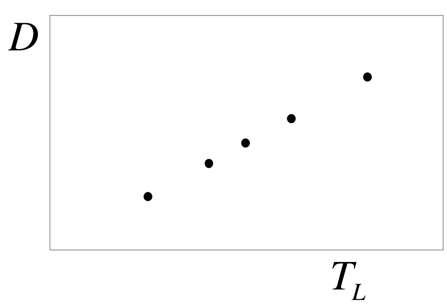
The duration of the excess rainfall is:

$$D = \frac{T_L}{5.5} \qquad D \text{ (hr)}$$

Measuring the surface runoff



$$\longrightarrow T_L = 0.75 C_t \left(L \times L_c\right)^{0.3}$$



$$\longrightarrow \quad D = \frac{T_L}{5.5}$$

Measuring the surface runoff

Procedures to derive the Snyder's UH:

Adjusting the basin lag to correspond the desired rainfall time (D'):

$$T_L' = T_L + 0.25(D' - D)$$

The UH base time is:

$$T_b = 3 + \frac{T_L'}{8}$$ T_b (day), T_L (hr)

the equation above is valid for large basins, for small basins, use T_b (hr) = 4 T_L'.

Measuring the surface runoff

Procedure to derive the Snyder's UH:

The peak direct runoff is:

$$Q_p = \frac{2.75 C_p A}{T_L'}$$ Q_p (m^3/s/cm), T_L (hr)

The time to peak flow occurrence is:

$$T_p = \frac{D'}{2} + T_L'$$

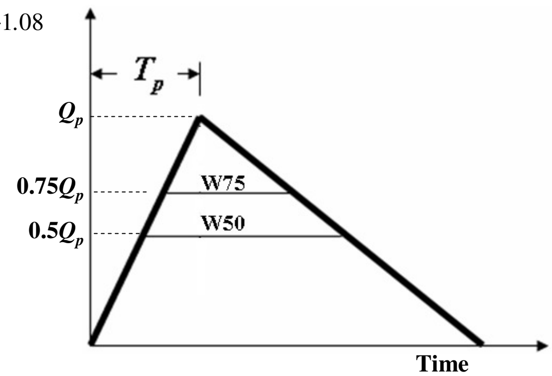
Measuring the surface runoff

Procedure to derive the Snyder's UH:

To assist in drawing the UH, compute W50 and W75 that are hydrograph time widths at 50 and 75% of the peak flow.

$$W50 = 5.87(Q_p / A)^{-1.08}$$

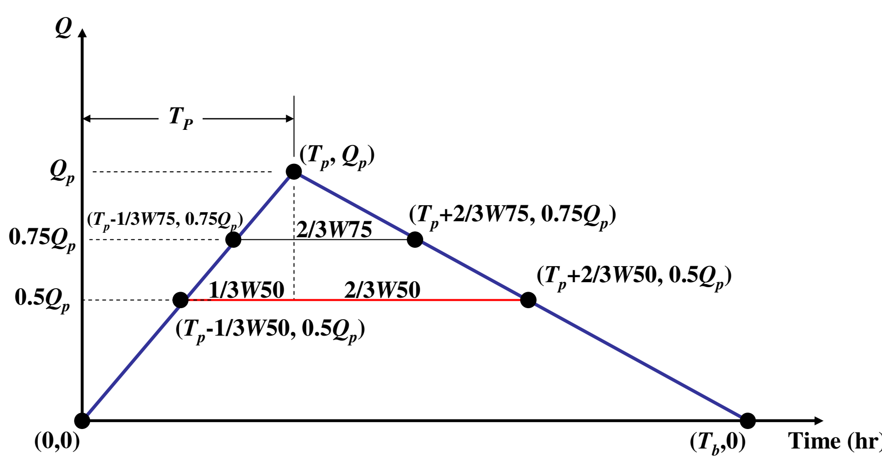
$$W75 = \frac{W50}{1.75}$$



Measuring the surface runoff

Procedure to derive the Snyder's UH:

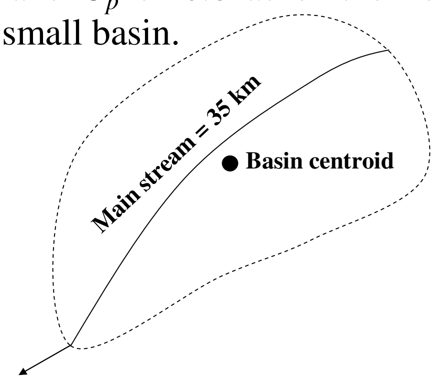
On the UH seven points will be available.



Measuring the surface runoff

Ex on Snyder's UH:

Develop a 2-hr unit hydrograph for the watershed shown. The basin area is 280km^2, and the distance along the main stream to the basin centroid nearest point is 20km. Use C_t of 1.5, and C_p of 0.8 as of the nearest gauged basin. Assume small basin.



Measuring the surface runoff

Soln: the basin lag is

$$T_L = 0.75 C_t (L \times L_c)^{0.3} = 0.75 \times 1.5 \times (35 \times 20)^{0.3} = 8\,hrs$$

The excess rainfall duration $D = \dfrac{T_L}{5.5} = \dfrac{8}{5.5} = 1.45\,hrs$

The desired UH is the 2-hr, so the excess rainfall is set at D' = 2 hrs, consequently the adjusted basin lag is:

$$T_L' = T_L + 0.25(D' - D) = 8 + 0.25(2 - 1.45) = 8.14\,hrs$$

and the UH base time is:

$$T_b = 4 \times 8.14 = 32.6\,hrs$$

Measuring the surface runoff

Soln:

The peak runoff is

$$Q_p = \frac{2.75 C_p A}{T'_L} = \frac{2.75 \times 0.8 \times 280}{8.14} = 75.7 \text{ m}^3\text{/s/cm}$$

The rise time (time to peak flow)

$$T_p = \frac{D'}{2} + T'_L = \frac{2}{2} + 8.14 = 9.14\, hrs$$

and $W50 = 5.87 (Q_p / A)^{-1.08} = 5.87 (75.7/280)^{-1.08} = 24.1\, hrs$

$$W75 = \frac{W50}{1.75} = \frac{24.1}{1.75} = 13.8\, hrs$$

Measuring the surface runoff

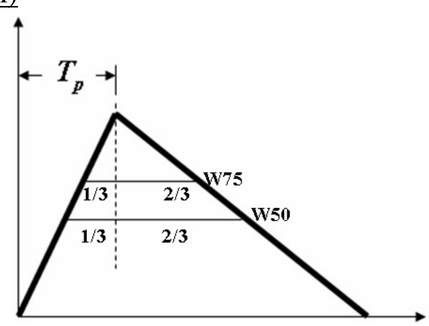
Soln:

the 1/3 of $W50 = 8.03 hrs$, and the 2/3 of $W50 = 16.07 hrs$

the 1/3 of $W75 = 4.6 hrs$, and the 2/3 of $W75 = 9.2 hrs$

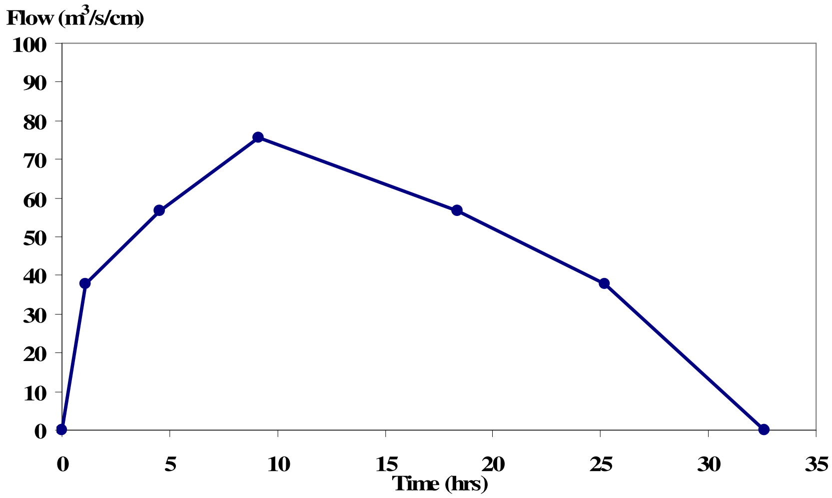
$T_p = 9.14\ hrs$.

Time (hrs)	Runoff (m^3/s/cm)
0.00	0.00
1.11	37.85
4.54	56.77
9.14	75.70
18.34	56.77
25.21	37.85
32.60	0.00



Measuring the surface runoff

The Snyder's synthetic 2-hr Unit Hydrograph:



Engineering Hydrology

110401454

Groundwater Hydrology

Instructor: Dr. Zeyad Tarawneh

Groundwater hydrology

Groundwater is part of the total water that is entrapped by impermeable layers called ***aquicludes***. Such aquicludes form the shape of the groundwater container (***aquifer***). While part of the groundwater may be rechargeable due to infiltration, other part is un-rechargeable.

The groundwater hydrology cares generally about studying the aquifers properties, groundwater movements, groundwater flow amount, and the drop in the groundwater table (drop in storage).

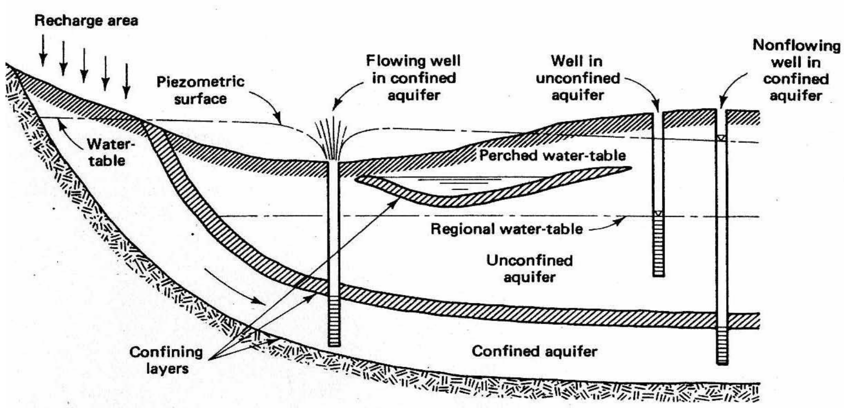
Groundwater hydrology

Groundwater ***aquifers*** are geological formations with sufficient permeability to allow the groundwater extraction (pumping out). In nature, such aquifers are either ***confined*** or ***unconfined***.

The ***confined aquifer*** is geological layer that is entrapped by two less permeable layers (two aquicludes) and the water flows as in closed conduits (pressurized pipes), while the ***unconfined aquifer*** has an upper saturated permeable layer with defined water table. The flow regime in such aquifer is similar to flow in open channels.

Groundwater hydrology

Types of aquifers



Types of aquifers.

Groundwater hydrology

The groundwater flow:

The groundwater flow characteristics depend on the permeability of the conveyance medium, and the hydraulic gradient (water head difference). The groundwater flow velocity is directly related to the hydraulic gradient within the aquifer. Darcy expressed the velocity as:

$$V = -k\,\frac{dh}{dr} = -k\;s$$

k: constant called the hydraulic conductivity,
dh: drop in hydraulic grade line between 2 observation points,
dr: horizontal distance between 2 observation points,
s: the hydraulic gradient.

Groundwater hydrology

Equilibrium analysis of the groundwater flow:

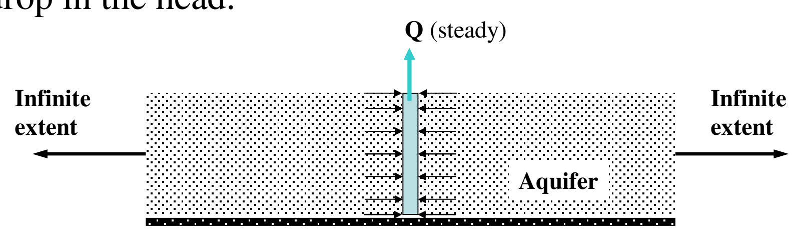
The equilibrium analysis to solve the Darcy equation assumes that:

- the flow rate from the aquifer is constant (*steady*),

- the well is screened through the entire aquifer depth,

- the aquifer is uniform of infinite extent (Isotropic),

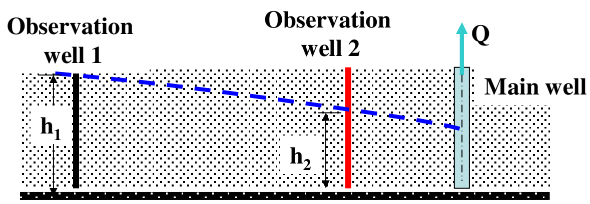
- the water is released immediately in response to a drop in the head.



Groundwater hydrology

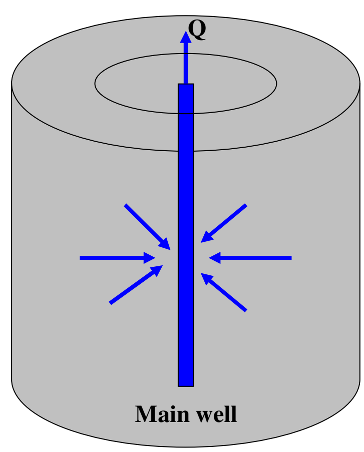
Observation wells:

To study the flow from the main groundwater well, an observation wells are introduced. The purpose of the observation well is to control the operation of the main well through supplying groundwater measurements.



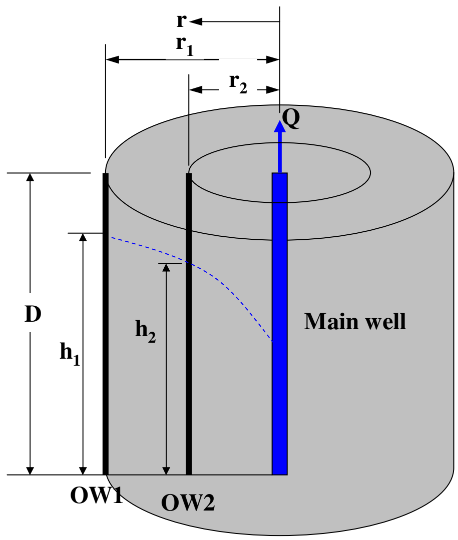
Groundwater hydrology

The groundwater is assumed to move towards the main well from all horizontal directions (steady radial flow).



Groundwater hydrology

Steady radial flow:



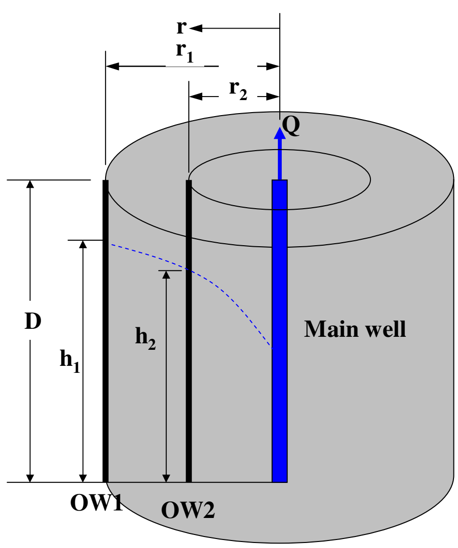
$$V = k\frac{dh}{dr}$$

$$Q = k\frac{dh}{dr}A$$

$$Q = k\frac{dh}{dr}(2\pi r D)$$

Groundwater hydrology

Steady radial flow:



$$Q = k\frac{dh}{dr}(2\pi r D)$$

$$\frac{dr}{r} = \frac{2\pi D k}{Q}dh$$

$$\int_{r_1}^{r_2}\frac{dr}{r} = \frac{2\pi D k}{Q}\int_{h_1}^{h_2}dh$$

Groundwater hydrology

Steady radial flow:

$$\int_{r_1}^{r_2} \frac{dr}{r} = \frac{2\pi Dk}{Q} \int_{h_1}^{h_2} dh$$

Check what will happen if the equilibrium analysis assumptions are not applicable

$$\ln(r_2) - \ln(r_1) = \frac{2\pi Dk}{Q}(h_2 - h_1)$$

Groundwater hydrology

Steady flow from the confined aquifer:

Solving the Darcy equation and using the simplifications stated through the assumptions of the equilibrium analysis, the groundwater flow rate from the confined aquifer of constant thickness *D* is:

$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\mathbf{ln}(r_2 / r_1)}$$

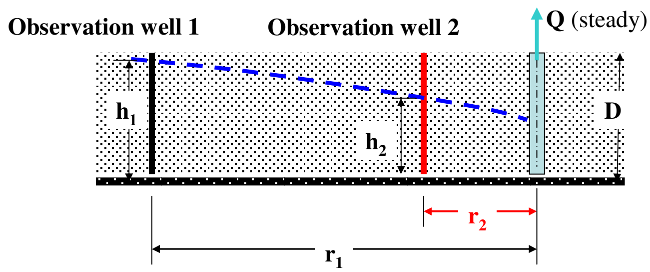
The term *kD* is called the aquifer transmissivity (*T*)
h_1 and h_2: the hydraulic water head at the observation wells 1 and 2,
r_1 and r_2: the radial distances to observation wells 1 and 2.

Groundwater hydrology

Steady flow from the confined aquifer :

$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\mathbf{ln}(r_2 / r_1)}$$

The distance r measured from the center line of the observation well to the centre line of the main well.



Groundwater hydrology

Steady flow from the unconfined aquifer:

In unconfined aquifers, the aquifer thickness D varies (not constant). If the thickness D is expressed in terms of the water head (h) that is measured from the underlying aquiclude (bottom layer), in that case the flow rate under the assumption of an equilibrium analysis is:

$$Q = \frac{2\pi k\left(h_2^2 - h_1^2\right)}{\mathbf{ln}(r_2 / r_1)}$$

Groundwater hydrology

Ex:

The flow from a main well in a confined aquifer of 15m thickness is 25L/s. If the water table elevations at two observations wells 50m and 20m away of the main well are 114.6m and 112.5m respectively, find the transmissivity of the aquifer?

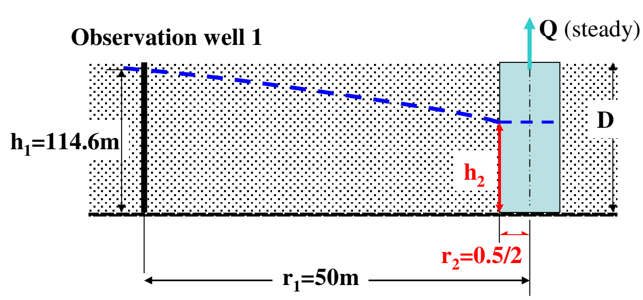
$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\ln(r_2 / r_1)} = \quad 0.025 = \frac{2\pi\, k\,(15)(112.5 - 114.6)}{\ln(20/50)}$$

k = 10m/day, and T = 150m^2/day.

Groundwater hydrology

Ex:

A main well of 25L/s flow has diameter of 0.5m and transmissivity of 150m^2/day, what is the height of the water table head at the main well if the water head at an observation well 50m away is 114.6m?



Groundwater hydrology

Soln:

$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\mathbf{ln}(r_2 / r_1)} =$$

$$0.025 = \frac{2\pi(150/86400)(h_2 - 114.6)}{\ln(0.25/50)}$$

The water table head at the main well is h_2 = 102.5m

Groundwater hydrology

Self test question:

A main well of 0.5m diameter penetrates a confined aquifer of k = 20m/day and thickness of 35m. The flow is pumped from the main well such that its water table is maintained at drawdown (drop) of 5m below the water table of an observation well that is 600m from the main well, what is the discharge from the main well?

Groundwater hydrology

The hydraulic conductivity in anisotropic aquifers:

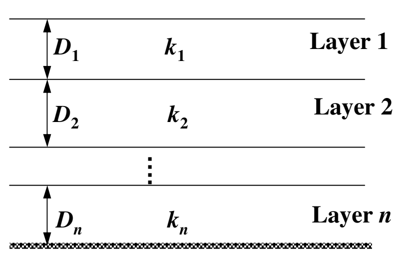
When the aquifer material varies either horizontally or vertically, then the aquifer is anisotropic and hence an average k should be used. This case is more realistic than assuming that the aquifer is totally isotropic (k is constant), however in reality, the aquifer contains materials that differ in properties in all directions.

To simplify the study in case of anisotropy, the variation in the k will be detailed in the horizontal and vertical direction.

Groundwater hydrology

The equivalent horizontal hydraulic conductivity:

Assume an aquifer of horizontal layers 1, 2, ..,n.

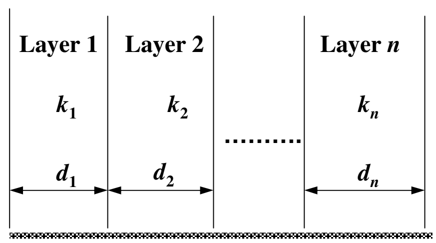


$$k_H = \frac{k_1 D_1 + k_2 D_2 + \dots\dots + k_n D_n}{D_1 + D_2 + \dots\dots + D_n}$$

Groundwater hydrology

The equivalent vertical hydraulic conductivity:

Assume an aquifer of vertical layers 1, 2, ..,*n*.



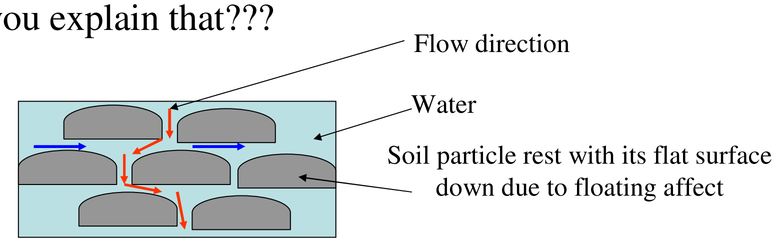
$$k_V = \frac{d_1 + d_2 + \ldots\ldots + d_n}{\dfrac{d_1}{k_1} + \dfrac{d_2}{k_2} + \ldots\ldots + \dfrac{d_n}{k_n}}$$

Groundwater hydrology

The relation between k_H and k_V:

In literature, it has been found that the horizontal hydraulic conductivity k_H is always greater than the vertical hydraulic conductivity k_V ($k_H / k_V \approx 2 - 10$). For clay soils the ratio may reach up to 100.

Can you explain that???



Drop in the groundwater table

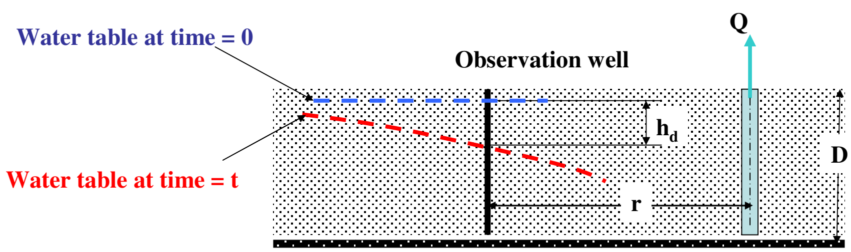
Nonequilibrium analysis:

For the case of the non-equilibrium analysis and given the flow rate, the drop in hydraulic head (drop in the water table level) is expressed by the Cooper-Jacob approximation as (h_d):

$$h_d = \frac{Q}{4\pi T} \ln\left(\frac{2.25 T\, t}{r^2\, S}\right)$$

h_d : the drop in water table (m),
t : the time (seconds),
r : distance between the main and the observation well
S: volume released per unit volume of the aquifer per unit drop in the water table (unit less).

Drop in the groundwater table



$$h_d = \frac{Q}{4\pi T} \ln\left(\frac{2.25 T\, t}{r^2\, S}\right)$$

Drop in the groundwater table

Ex:

An aquifer of T = 150m^2/day, S = 10^{-4} provides flow of 25L/s to a main well. Compute the drop (h_d) at an observation well 20m away from the main well after 1day and 30days of pumping?

Soln: Applying the Cooper-Jacob approximation for h_d then:

$$h_d = \frac{Q}{4\pi T}\ln\left(\frac{2.25T\,t}{r^2\,S}\right)$$

$$h_d = \frac{0.025}{4\pi\left(\frac{150}{86400}\right)}\ln\left(\frac{2.25(150)t}{(20)^2\times10^{-4}}\right)$$

Drop in the groundwater table

Substituting 1day and 30days for t in the equation (h_d), the results are shown below:

t (days)	h_d (m)
1	10.36
30	14.26

What do you observe?

Drop in the groundwater table

Ex:

A confined well produces flow through an aquifer of T = 200m^2/day. The volume released per unit volume of aquifer per unit drop in the water table is 0.008. Calculate the 2 days drop at an observation well 40m away from the main well when the flow for the first day is 100L/s while for the second day is 80L/s. ?

Soln: Applying the Cooper-Jacob approximation for h_d then:

$$h_d = \frac{Q}{4\pi T} \ln\left(\frac{2.25\,T\,t}{r^2\,S}\right)$$

Drop in the groundwater table

The drop for the first day at Q of 100L/s =

$$h_d = \frac{0.1}{4\pi(200/86400)} \ln\left(\frac{2.25(200)(1)}{(40)^2(0.008)}\right) = 12.238m$$

The drop for the second day at Q of 80L/s =

= h_d at Q of 80L/s for t = 2 days – h_d at Q of 80L/s for t = 1day

$$= \frac{0.08}{4\pi(200/86400)} \ln\left(\frac{2.25(200)(2)}{(40)^2(0.008)}\right) - \frac{0.08}{4\pi(200/86400)} \ln\left(\frac{2.25(200)(1)}{(40)^2(0.008)}\right) = 1.906m$$

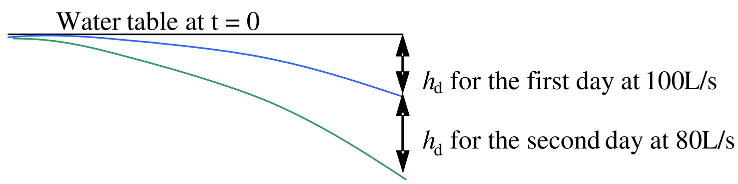
Drop in the groundwater table

The total (cumulative) drop over the whole 2 days =

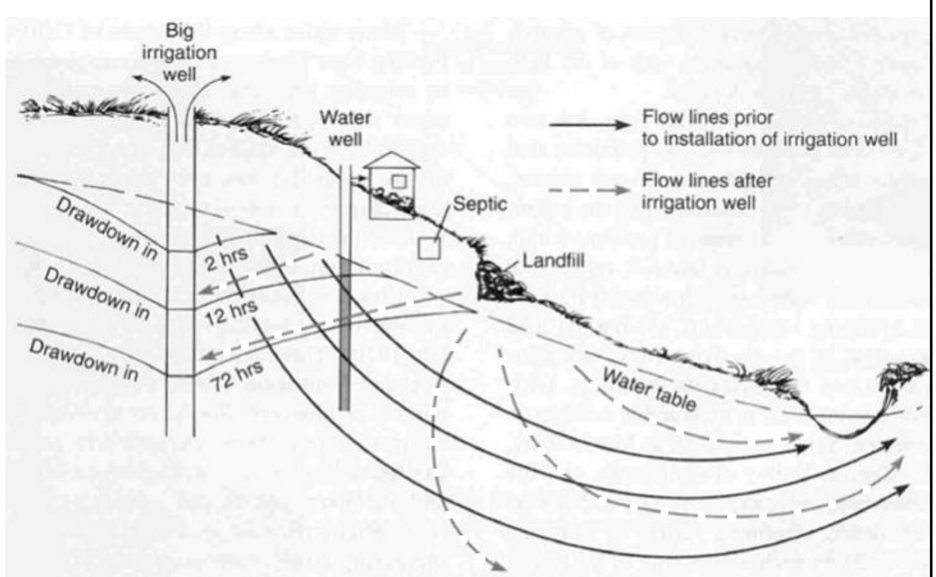
= h_d at 100L/s for the first day + h_d at 80L/s for the second day

= 12.238 + 1.906

= 14.144m



Drop in the groundwater table



Drop in the groundwater table

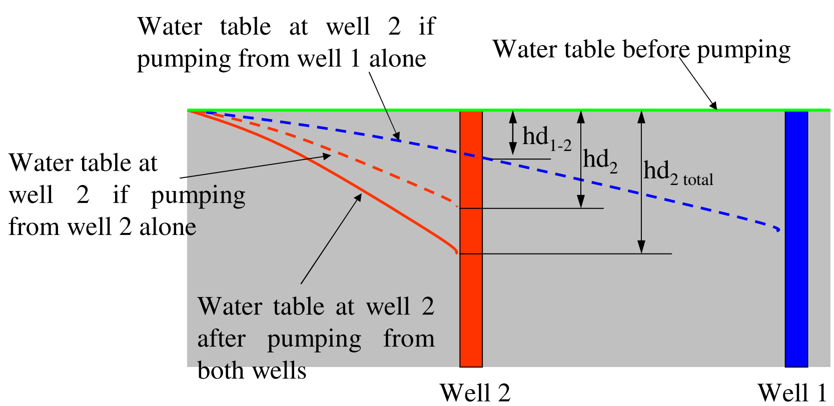
Multiple well system:

When there are multiple active wells in the same aquifer, then pumping from individual wells will add cumulative effect (multiple wells together) on the groundwater table, i.e. each well will affect (drop) the water head at other wells. In reality, a minimum distance between active wells is kept to reduce such effect, such distance is called the well influence distance.

The well influence distance is defined as the radial distance from the well center such that the water table drop is kept nearly zero!!! when the well is under operation.

Drop in the groundwater table

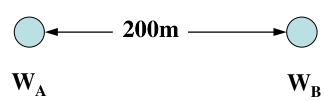
Observe the effect of well 1 on well 2 just.



Drop in groundwater level

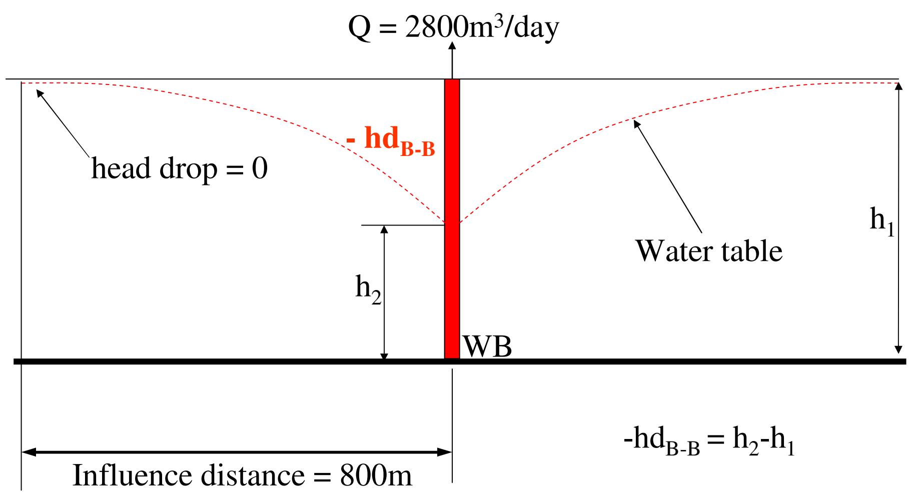
Ex:

Two pumping wells in confined aquifer with 800m influence distance are located as shown. Water is pumped from wells A and B at steady rates of 5220 and 2800m^3/day respectively. Calculate the total head drop at well B given aquifer T is 2400m^2/d. Well B has 40cm diameter.



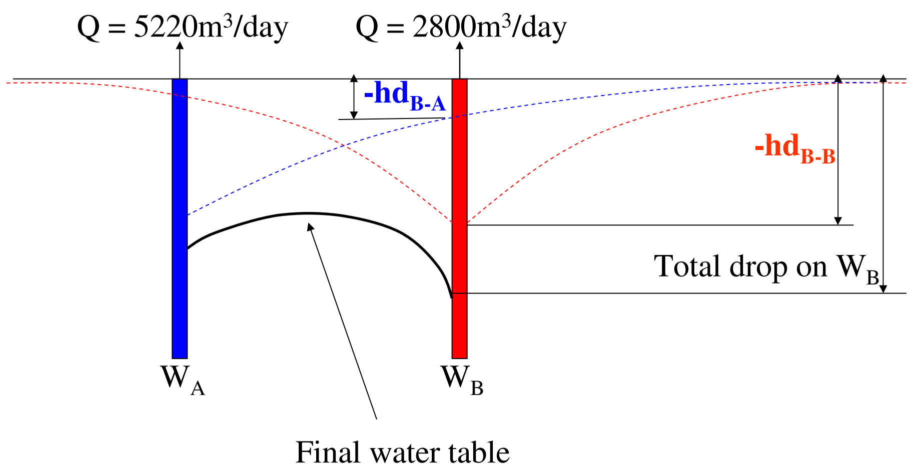
Drop in groundwater level

Head drop at well B from its self (hd_{B-B}).



Drop in groundwater level

Influence on well B from its self and from well A.



Drop in groundwater level

Soln:
$T = 2400/86400 = 0.0278 \text{m}^2/\text{s}$. $Q_A = 5220 \text{m}^3/\text{d} = 0.06 \text{ m}^3/\text{s}$.
$Q_B = 0.032 \text{m}^3/\text{s}$.

The total head drop at W_B = head drop at W_B from W_B (hd_{B-B}) + head drop at W_B from W_A (hd_{B-A}).

The drop on W_B from its self (hd_{B-B}) is estimated from:

$$Q = \frac{2\pi T(h_2 - h_1)}{\ln(r_2 / r_1)}$$

$$Q_B = \frac{2\pi \times 0.0278(-hd_{B-B})}{\ln(0.2/800)} = 0.032 \longrightarrow hd_{B-B} = 1.52\text{m}$$

Drop in groundwater level

Soln:
The drop on W_B from W_A is $hd_{B\text{-}A}$:

$$Q = \frac{2\pi T(h_2 - h_1)}{\mathbf{ln}(r_2 / r_1)}$$

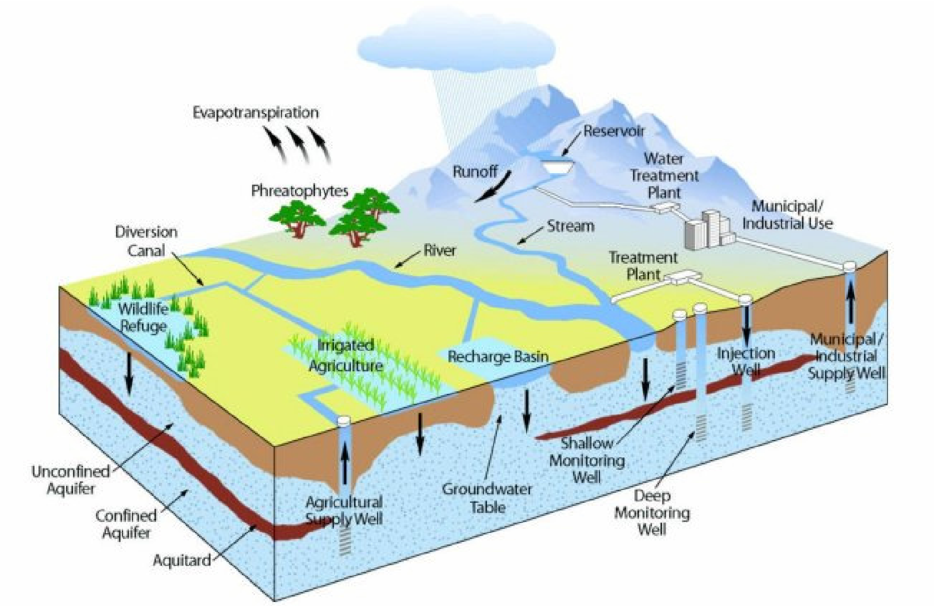
$$Q_A = \frac{2\pi \times 0.0278(-hd_{B-A})}{\ln(200/800)} = 0.06 \longrightarrow hd_{B\text{-}A} = 0.48\text{m.}$$

Total drop at well B = $hd_{B\text{-}B} + hd_{B\text{-}A} = 1.52 + 0.48 = 2$m.

Groundwater artificial recharge

Definition:
The term groundwater artificial recharge refers to the process of transferring the surface water to the groundwater aquifer by human interference. The main concept behind the artificial recharge is to construct simple structures to entrap surface water that will be eventually transferred to the groundwater after being infiltrated through the soil layers. Therefore, the recharge process depends on the quantity of the surface water stored and the soil properties as well (fast versus slow artificial recharge will depend on the soil void ratio, soil particle size, soil moisture content).

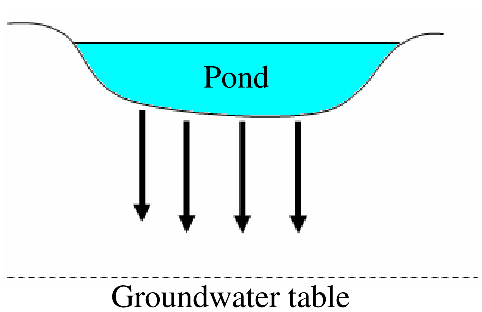
Groundwater artificial recharge



Groundwater artificial recharge

Techniques of artificial recharge:

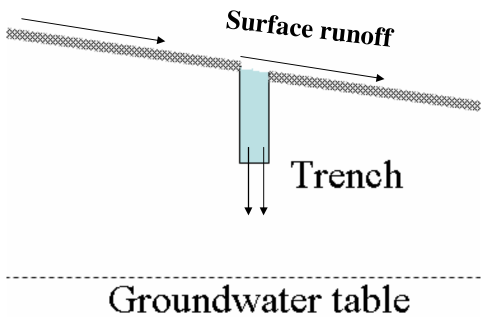
- Infiltration pond (recharge basin): are natural soil ponds placed next to major surface runoff streams to store surface water and allow the infiltration through soil to the underlying unconfined aquifer.



Groundwater artificial recharge

Techniques of artificial recharge:

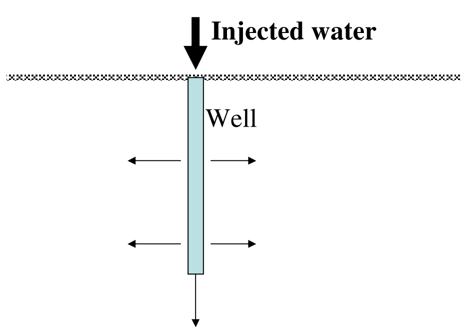
- Trenches: are structures in natural soil placed sloppy lands to intercept surface runoff and store water and allow the infiltration through soil to the underlying unconfined aquifer.



Groundwater artificial recharge

Techniques of artificial recharge:

- Injection wells: are structures similar to bore wells where surface water is pressure or gravity injected to supply water to ground aquifers.



Groundwater artificial recharge

Advantages of artificial recharge:

- It utilizes the surplus surface water to enhance the groundwater storage and eventually increases the safe yield.
- It requires simple and low cost structures to store water for recharge.
- It has negligible losses (no evaporation).
- It improves the groundwater quality through diluting potential groundwater solids content.

Groundwater artificial recharge

Ex:
Observe the recharge % of the total annual inflow for the Wala dam reservoir.

Year	Total inflow (m^3)	Spilling (m^3)	Recharged water (m^3)	%
2008	1,349,793	------	1,220,721	90
2009	16,381,583	6,754,228	8,777,947	54
2010	34,570,535	25,173,738	9,617,735	28
2011	3,223,646	------	2,145,678	67

Introduction to water resources

The science of water resources is the water science that focuses on studying the availability of water stored in a region to cover the demand on water for human activities like the domestic need (drinking, cooking and cleaning), industrial activities need (food industry, paper industry, tanning industry, structure industry, etc), agricultural activities need, and recreational activities need.

In general water is available from the following sources: surface water (rivers, springs, natural and artificial lakes), groundwater aquifers, treated wastewater, and fresh water production using membrane filtration.

Water resources classification

All water resources are classified either **traditional** or **non-traditional** water sources. Traditional water sources are those evolved due to natural events like precipitation or snow-melt (no human interference) like flow in rivers and natural lakes. By definition, all groundwater sources are traditional sources.

On the other hand, the non-traditional water resources are those evolved due to human interference (man-made structures) like treated wastewater from treatment plants, and the freshwater production from desalting seawater and brackish water using membrane filtration. In Jordan, water from both traditional and non-traditional sources is available.

Water resources classification

It should be noted that all the **non-traditional** water resources are renewable resources, for example the fresh water production from seawater desalination projects (imagine the size of seas and oceans).

As a traditional water source, while part of the groundwater sources is considered renewable, other part is considered non-renewable sources (for example, the Disi aquifer is a non-renewable groundwater source).

Surface water sources from rivers, greeks, natural and artificial lakes and from the snowmelt are renewable water sources, however water amounts that can be utilized depend on the precipitation amount and the amount of water withdrawn.

Water resources facts (worldwide)

Table 1. Annual renewable water per person

	Renewable annual freshwater available (m^3/person)	Rank
Water-scarce countries (20 countries)		
Jordan	327	10
Water-stressed countries (8 countries)		
Egypt	1 123	23
Cyprus	1 282	25
Water-abundant countries		
Lebanon	1 818	31
Syria	2 087	36
Turkey	3 626	61
United States	9 913	91
Canada	108 900	141

The study is based on 149 countries worldwide.

Utilized water resources in Jordan

The following table shows the distribution of the annual amounts of water that can be utilized from different sources in Jordan:

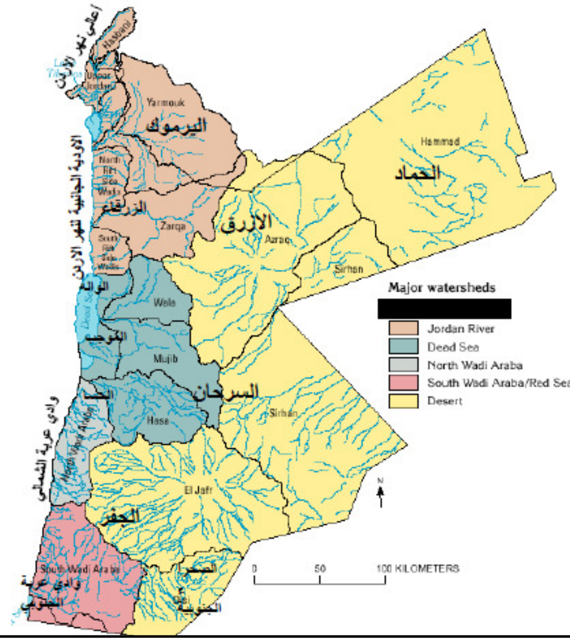
Source	amount (Mm^3)
Renewable groundwater	280
Non-renewable groundwater	140
Surface water	750
Treated wastewater	100
Brackish water (ready for desalting)	70

Surface water in Jordan

An other primary source of water in Jordan is the surface water from surface basins (large area that contributes surface water). The following table refers to major surface basins in Jordan.

Basin	annual surface water flow (Mm^3)
Yarmouk river basin	166
Zarqa river basin	84
Mujib & Wala basin	102
Dead sea side wadis	43
Hesa	43
Jafr	13
Azraq	41
Northern wadi araba	46

Surface basins in Jordan



Distribution of water usage in Jordan

Water from different sources in Jordan is used mainly to cover the needs of domestic purposes, agriculture and industrial activities. The following table shows the distribution of water usage in Jordan for the year 2005 versus competing sectors.

Sector	amount used (Mm^3/yr)	% of water use
Domestic	291	31
Agriculture	604	64
Industrial	38	4
Live-stock	8	1
Total	941	100

The stressed water resources in Jordan

Due to the limited water resources in Jordan, the increased demand on water for domestic, agriculture and industrial activities has exceeded the available water sources. The following table shows future scenarios about the demand versus the supply in Jordan.

Year	Total demand (Mm^3)	Total supply (Mm^3)	Deficit (Mm^3)
2010	1383	1054	329
2020	1602	1152	450
2040	2236	1549	687

Introduction to surface water resources

Surface water resources in Jordan contribute about 38% of the national water balance. The majority of the surface water in Jordan comes from winter floods collected in major dams and stream flows from the Yarmouk river, Zarqa river and other eastern tributaries (Wadis) of the lower Jordan river.

Such water source is considered renewable, however surface water sources in Jordan are exploited due lack of precipitation in recent years and the increased demand on water.

From water quality perspective, surface water needs further treatment for domestic purposes when compared to groundwater sources (why?).

Surface water usage

Surface water resources in Jordan are used for different purposes including:

1. Water supply for irrigation use, mainly in the Jordan valley (about 30000 hectares) and highlands (about 4000 hectares).
2. Water supply for domestic use (Zai water treatment plant is provided by water from Eastren Ghor Canal).
3. Water source for industry (Potash Arab Co. is supplied partially by its water needs from the Mujib dam).
4. Hydro-power generation (King Talal dam).
5. Groundwater recharge (Wala dam, Sewaqa dam).

Surface water resources

Major rivers and wadis in Jordan.

River	**Basin area (Km^2)**	**Average historic annual flow (Mm^3)**	**Water utilized (Mm^3)**
Jordan	18194	1400	----
Yarmouk	6974	440 (reduced to 360)	100
Zarqa	4154	85	Fully utilized
Wadi El-Arab	246	28	Fully utilized
Wadi Ziglab	100	10	Fully utilized
Wadi Kafrain	159	17	Fully utilized
Wadi Mujib	4380	83	Fully utilized

Surface water resources

As can be seen from the previous table, the Yarmouk river is considered as the main, the largest, and the most important surface water resource in Jordan and considered as a vital national resource. Recall that the Yarmouk river is multi-share sources (Jordan about $100Mm^3$, Syria about $160Mm^3$, and others about $100Mm^3$).

It should be noted that Jordan cannot use the water from Jordan river. The river natural freshwater flow has been interrupted and abstracted before reaching Jordanian lands, where only return irrigation flow and saline water remains.

Surface water resources

Major reservoirs in Jordan.

Dam	Catchment area (Km^2)	Live storage (Mm^3)	Purposes	Water resources
Wadi El-Arab	262	17	Irrigation, domestic water supply, power generation.	King Abdullah Canal in winter and floods of Wadi El-Arab.
King Talal	3,700	75	Irrigation, power generation.	Zarqa River and As-Samra wastewater treatment plant.
Al Karameh	61	55	Irrigation.	Surplus water from King Abdullah Canal in winter.
Kafrein	163	9	Irrigation, artificial recharge.	Flood and base flow from wadi Kafrein.

Surface water resources

Major reservoirs in Jordan.

Dam	Catchment area (Km^2)	Storage (Mm^3)	Purposes	Water resources
Wehdah	6974	100	Irrigation, domestic water supply.	Yarmouk river flow, winter flood.
Mujib	4380	32	Irrigation, domestic and industrial water supply.	Mujib valley springs, winter flood.
Al tannur	2160	16	Irrigation.	Hesa valley springs, winter flood.
Wala	1770	9	Irrigation, domestic and industrial water supply, groundwater recharge.	Winter flood.

In addition to major dams, there are 18 micro-dam of $31Mm^3$ total capacity, the largest among are Rowyshed dam of $10Mm^3$, Bayer dam of $5Mm^3$, and Qatraneh dam of $4.2Mm^3$.

Surface water resources

Mujib dam reservoir in Jordan.

Surface water resources

Winter flood at spillway of Wala dam.

Surface water storage

Reservoirs:

Reservoirs are large artificial lakes created by barriers (dams) to entrap surface water from natural streams to store and release water when needed. Reservoirs are classified according to the purpose into single-purpose reservoirs (Al Karameh dam reservoir for irrigation) and multi-purpose reservoirs (King Talal dam reservoir for irrigation and power generation).

Two major issues related to reservoirs are: to estimate the current storage capacity of existed reservoir, and to estimate the required capacity to meet future needs of water.

Surface water storage

Reservoir purposes:

Reservoirs are built to store and release water for several purposes including:

- Supply fresh water for domestic use,
- Supply water for irrigation,
- Flood control,
- Hydropower generation,
- Recreational purpose, and
- Creating positive impact on the environment.

Surface water storage

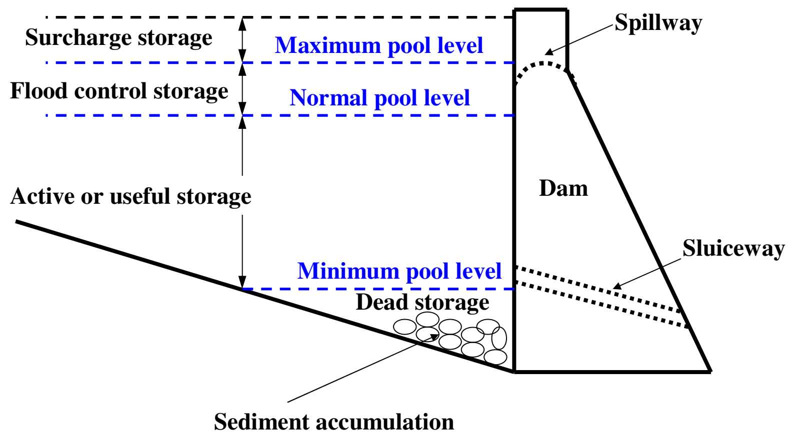
Reservoir storage components:

Reservoir storage consists of following components:

- Normal pool level,
- Minimum pool level,
- Active or useful storage,
- Dead storage,
- Surcharge storage, and
- Flood control storage.

Surface water storage

Reservoir storage components:



Surface water storage

Reservoir storage yield:

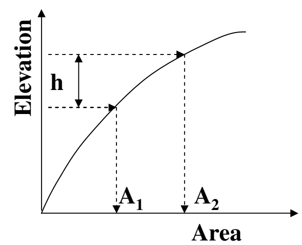
- Yield from a reservoir: the water amount that can be withdrawn from a reservoir in a specified period of time.
- Safe yield (firm yield): the maximum water volume can be supplied in a specified period of time during critical period (dry season).
- Secondary yield: the water volume that is available during high inflow season.

Surface water storage

Storage capacity of existed reservoir:

The trapezoidal formula is one of several methods used to estimate the current storage capacity of existed reservoir. It simply relies on estimating the water surface area from elevation-area curves (contour areas at h contour interval) and then the volume of water stored between two contours (surface areas A_1 and A_2) is given as:

$$\Delta V_1 = \frac{h}{2}\left(A_1 + A_2\right)$$



Surface water storage

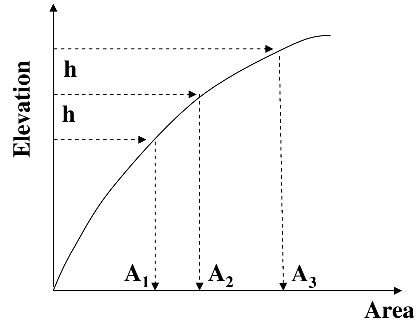
Storage capacity of existed reservoir:

The total storage volume (V) is the sum of sub-volumes between contour areas:

$$\Delta V_1 = \frac{h}{2}\left(A_1 + A_2\right)$$

$$\Delta V_2 = \frac{h}{2}\left(A_2 + A_3\right)$$

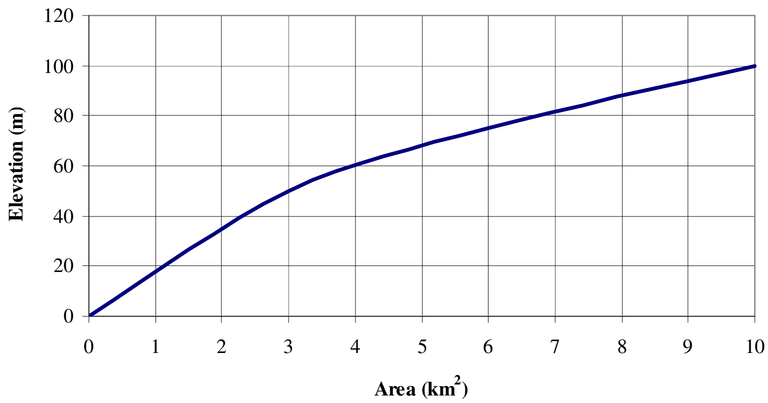
$$V = \Delta V_1 + \Delta V_2 + ...$$



Surface water storage

Ex:

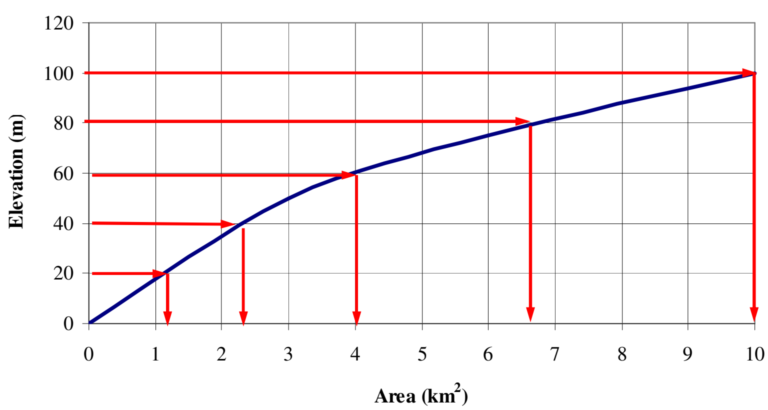
From the given elevation-area curve find the total storage volume (V) of an existed reservoir.



Surface water storage

Soln:

To compute the total storage volume (V) of the existed reservoir, contour interval of 20 is selected. At elevation 0m the area A_1 is 0km2, at 20m A_2 is 1.2km^2, at 40m A_3 is 2.3km^2, and so on..



Surface water storage

Soln:

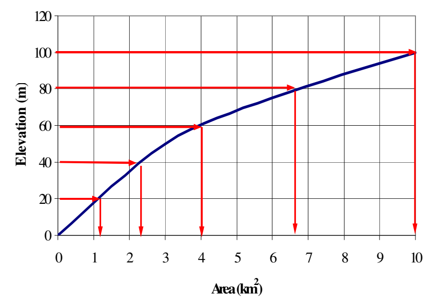
$$V = \Delta V_1 + \Delta V_2 + ...$$

$$V = \frac{20}{2}(0+1.2)+\frac{20}{2}(1.2+2.3)+\frac{20}{2}(2.3+4)$$

$$+\frac{20}{2}(4+6.7)+\frac{20}{2}(6.7+10)$$

$$=384 m.km^2$$

$$=384 Mm^3$$



Surface water storage

Storage capacity determination:

The storage capacity determination for non-existed reservoir is an important key for well managing water resources systems. The storage capacity is function of two elements: the inflow water amount (supply) and the outflow amount (demand or release).

In the next few slides, the active storage or the useful storage capacity will be determined. The size of the active storage highly relies on dry period analysis (critical period).

Surface water storage

Storage capacity determination:

In literature, the active storage capacity of reservoirs is determined using four methods:

1- The mass curve method (Ripple method).

2- Sequent peak method (analytical method) .

3- Operation approach.

4- Optimization approach.

For the purpose of this course, the first two methods will be discussed.

Surface water storage

Storage capacity determination:

The mass curve method (Ripple method) is used to estimate the active storage capacity of reservoirs when the demand on water (release) is constant. In the mass curve, the cumulative inflow determines the total supply, while the cumulative constant demand represents the total withdrawn. Our target is to maintain storage for the incoming flows during wet periods to overcome the largest deficit between the demand and the little inflow (little supply) during the dry periods.

The following example will show detailed solution.

Surface water storage

Ex:

Use the mass curve method (Ripple method) to estimate the active storage capacity of a reservoir that will be installed on a river with yearly inflows as shown in the table to overcome a constant demand on water of 70000m^3/yr.

Year	Inflow (m^3/yr)
2000	60000
2001	126000
2002	19000
2003	28000
2004	107000
2005	140000
2006	66000
2007	14000
2008	40000
2009	149000
2010	51000

Surface water storage

Soln:

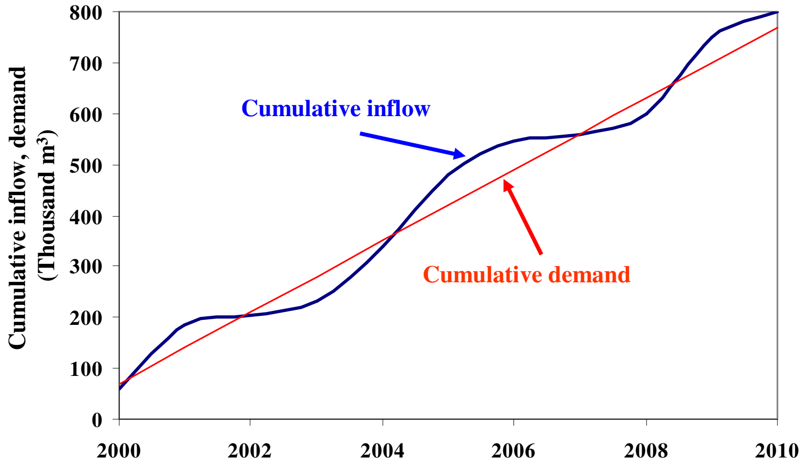
Step1: Calculate the cumulative inflows and cumulative demand.

Year	Inflow m^3	Cumulative inflow m^3	Demand m^3	Cumulative demand m^3
2000	60000	60000	70000	70000
2001	126000	186000	70000	140000
2002	19000	205000	70000	210000
2003	28000	233000	70000	280000
2004	107000	340000	70000	350000
2005	140000	480000	70000	420000
2006	66000	546000	70000	490000
2007	14000	560000	70000	560000
2008	40000	600000	70000	630000
2009	149000	749000	70000	700000
2010	51000	800000	70000	770000

Surface water storage

Soln:

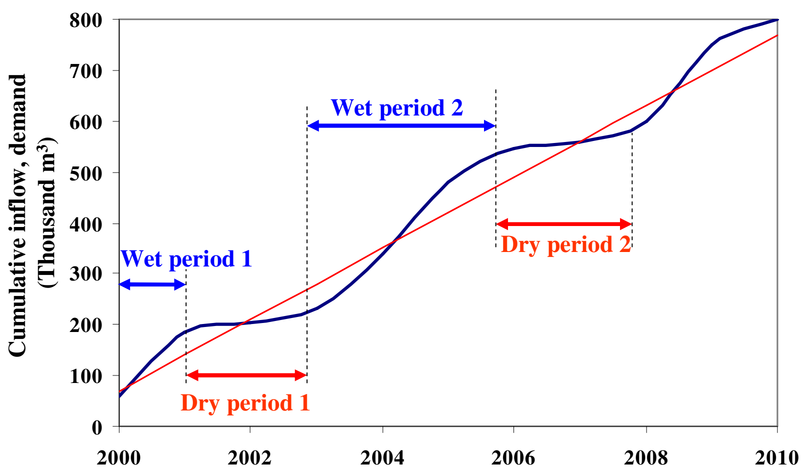
Step2: Plot the cumulative inflows and cumulative demand.



Surface water storage

Soln:

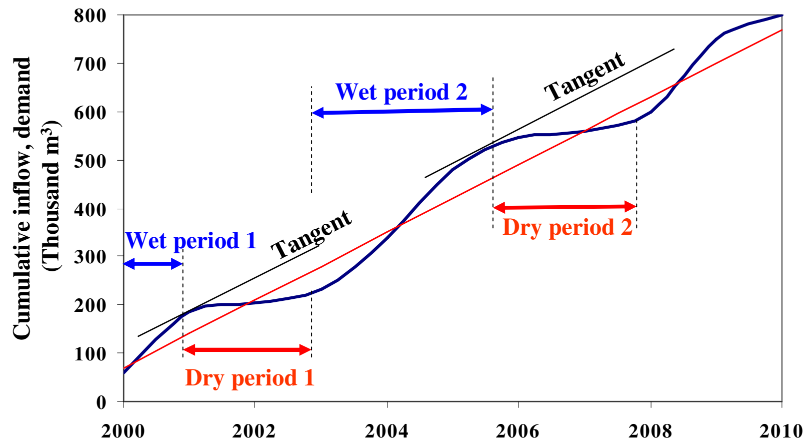
Step3: Locate dry and wet periods.



Surface water storage

Soln:

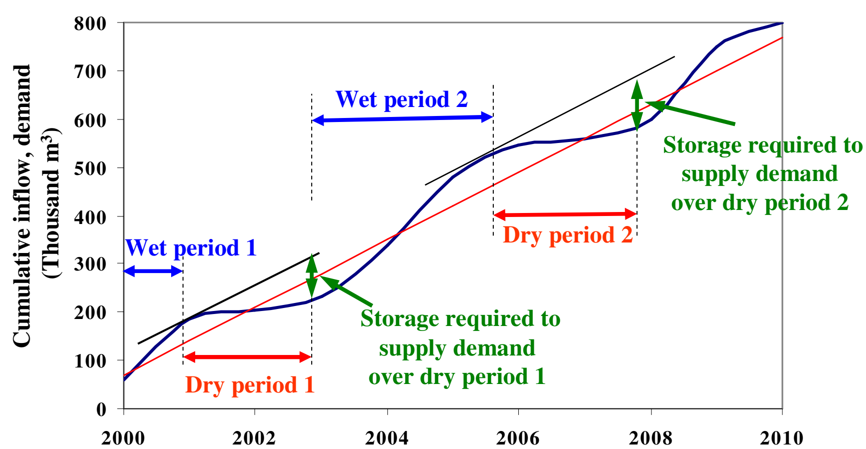
Step4: Construct tangents (parallel to demand) at the beginning of dry periods.



Surface water storage

Soln:

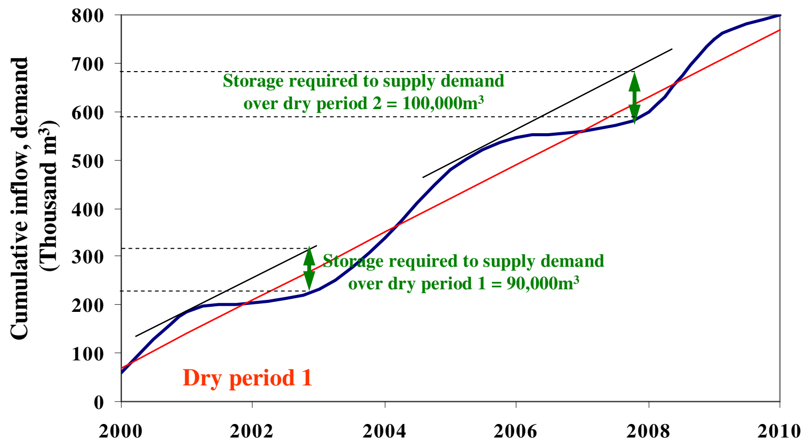
Step5: Find the storage required to supply the demand over the dry period.



Surface water storage

Soln:

Step6: Find the critical (maximum) storage required to supply the demand over the critical dry period. Storage = 100,000m^3.



Surface water storage

Storage capacity determination:

The sequent peak method is used to estimate the active storage capacity of reservoirs when the demand on water varies with time. In this method, the cumulative inflow determines the total supply, while the cumulative variable demand represents the total withdrawn. Our target is to maintain storage for the incoming flows during wet periods to overcome the largest deficit between the demand and the little inflow during the dry periods.

The following example will show detailed solution.

Surface water storage

Ex:

Use the sequent peak method to estimate the active storage capacity of a reservoir that will be installed on a river with yearly inflows as shown in the table to overcome the yearly demand on water as shown.

Year	Inflow (m^3/yr)	Demand (m^3/yr)
2000	60000	50000
2001	126000	75000
2002	19000	81000
2003	28000	77000
2004	107000	86000
2005	140000	66000
2006	66000	92000
2007	14000	44000
2008	40000	53000
2009	149000	51000
2010	51000	93000

Surface water storage

Soln:

Step1: Calculate the cumulative storage = Σ (inflow – demand).

Year	Inflow m^3	Demand m^3	Yearly storage m^3	Cumulative storage m^3	
2000	60000	- 50000	10000	10000	
2001	126000	75000	51000	61000	Surplus storage
2002	19000	81000	-62000 +	-1000	
2003	28000	77000	-49000	-50000	Deficit storage
2004	107000	86000	21000	-29000	
2005	140000	66000	74000	45000	Surplus storage
2006	66000	92000	-26000	19000	
2007	14000	44000	-30000	-11000	
2008	40000	53000	-13000	-24000	Deficit storage
2009	149000	51000	98000	74000	
2010	51000	93000	-42000	32000	

Surface water storage

Soln:

Step2: Determine the reservoir storage capacity from the analysis of the cumulative storage. The reservoir storage capacity is the difference between the surplus storage and deficit storage.

For dry period 1, the reservoir active storage =

= 61000 – (-50000) = 111000 m^3.

For dry period 2, the reservoir active storage =

= 45000 – (-24000) = 69000 m^3.

The critical storage is 111000m^3 which the reservoir active storage.

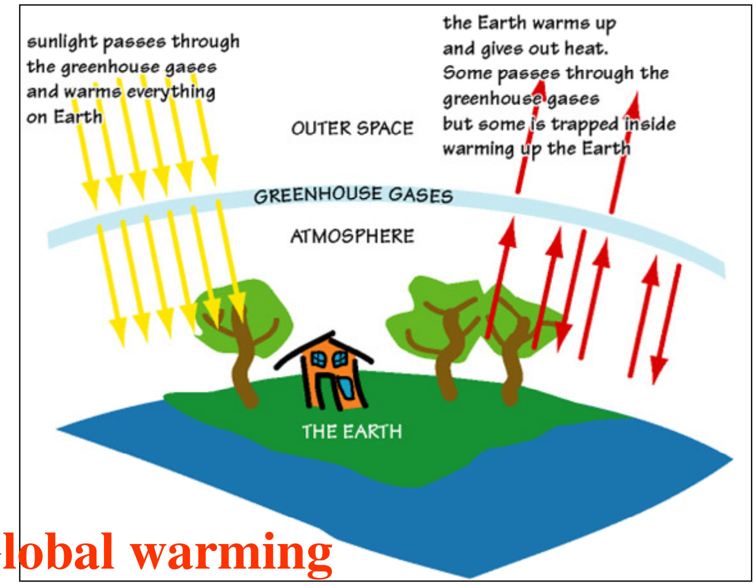
Surface water storage

Water losses from surface reservoirs:

Besides to sedimentation problem, water in surface reservoirs is exposed to losses including evaporation and leakage. The following measures can be adopted to reduce water losses:

- Constructing deep reservoirs to reduce evaporation,
- Planting tall trees around the reservoir to reduce the wind speed and hence reducing the potential evaporation,
- Covering the reservoir with plastic sheets (for small reservoirs).
- Removing weeds and un useful water plants.

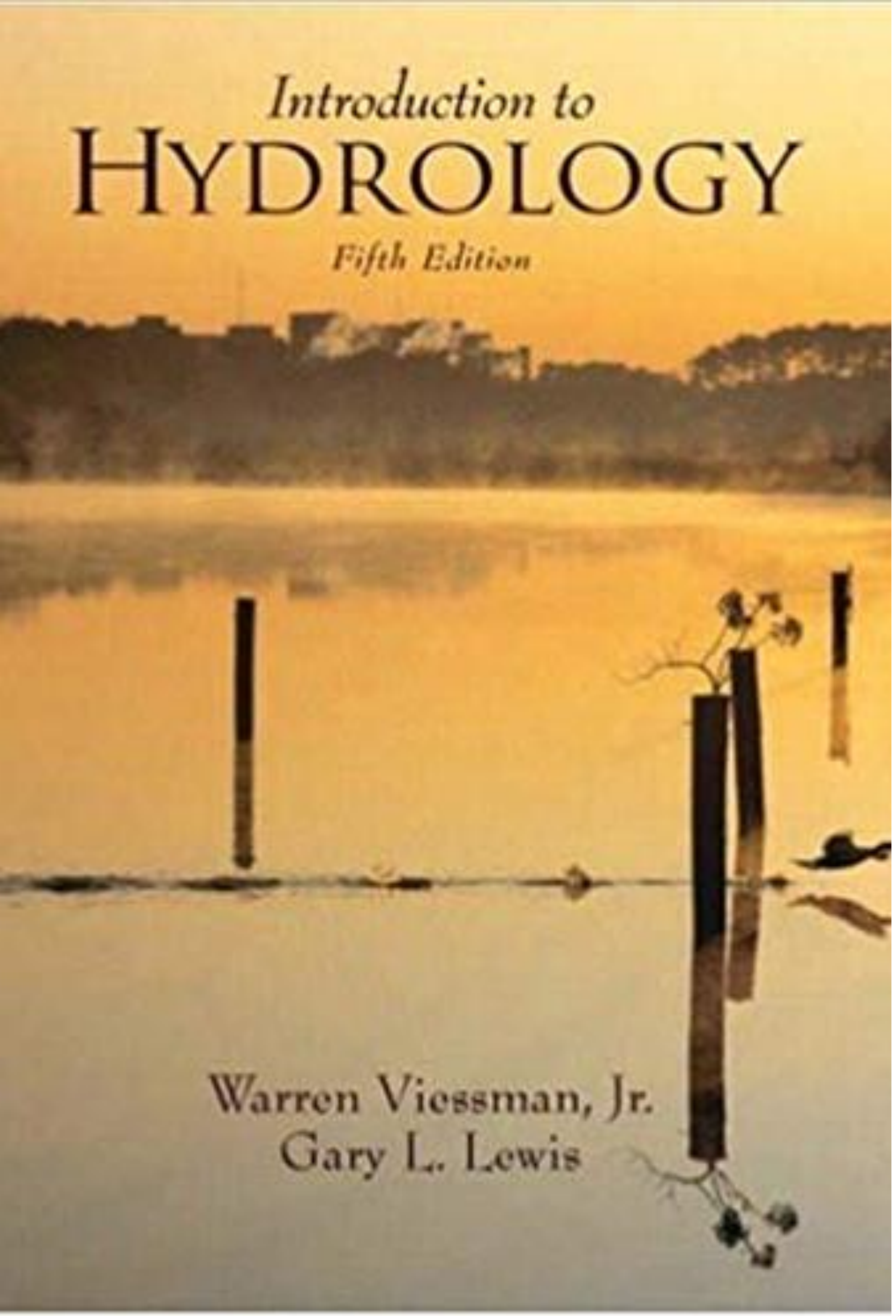
Globe issue related to hydrology



Global warming

Engineering Hydrology
CE 454

Lectures 1+2 . Introduction, hydrologic cycle, hydrologic budget



Textbook

- Introduction to hydrology. Viessman W. (2002), 5th edition, Prentice Hall.

Course Description

Hydrology is a basic civil engineering course that enables CE students to understand and perform engineering computations related to water quantities from rainfall or snow melt. In specific, topics related to hydrologic cycle and budget, statistical methods in hydrology, surface and groundwater flow computation will be addressed.

Course Learning Objective

Upon successful completion of the course you should be able to **use principles of engineering to compute the rain and groundwater flow**.

HYDROLOGY - definition

- **Hydrology** (from Greek: ὕδωρ, "hýdōr" meaning "water"; and λόγος, "lógos" meaning "study") is the scientific study of the movement, distribution, and quality of water on Earth and other planets, including the water cycle, water resources and environmental watershed sustainability.

Definitions- Cont.

- Hydrology, scientific discipline concerned with the waters of the Earth, including their occurrence, distribution, and circulation via the hydrologic cycle and interactions with living things.

- Hydrology is an essential field of science since everything from tiny organisms to individuals to societies to the whole of civilization - depends so much on water.

HYDROLOGY | branches

Chemical Hydrology

Study of chemical characteristics of water

Water Quality

Chemistry of water in rivers and lakes, both of pollutants and natural solutes

Eco Hydrology

Study of interactions of living organisms and the hydrologic cycle

Hydrogeology

Study of the distribution and movement of groundwater in the soils and rocks of the Earth’s crust

Hydrometeorology

Study of the transfer of water and energy between land and water body surfaces and the lower atmosphere

Surface Hydrology

Study of hydrologic processes that operate at or near Earth's surface

Drainage Basin Management

Covers water-storage, in the form of reservoirs, and flood-protection

Problems in Hydrology

- Extreme weather and rainfall variation
- Streamflow and runoff considerations
- River routing and hydraulic conditions
- Overall water balances - local and global scales
- Flow and hydraulics in pipes, streams and channels
- Flood control and drought measures
- Watershed management for urban developmen

A school bus drives through floodwater in Houston, Texas
September,20,2019

Arkansas
River
Flooding

May, 2019

Hydrology Application

- Calculation of rainfall.
- Calculating surface runoff and precipitation.
- Determining the water balance of a region.
- Determining the agricultural water balance.
- Mitigating and predicting flood, landslide and drought risk.
- Real-time flood forecasting and flood warning.
- Designing irrigation schemes and managing agricultural productivity.
- Part of the hazard module in catastrophe modeling.
- Providing drinking water.
- Designing dams for water supply or hydroelectric power generation.
- Designing bridges.
- Designing sewers and urban drainage system.
- Assessing the impacts of natural and anthropogenic environmental change on water resources.
- Estimating the water resource potential of river basins.

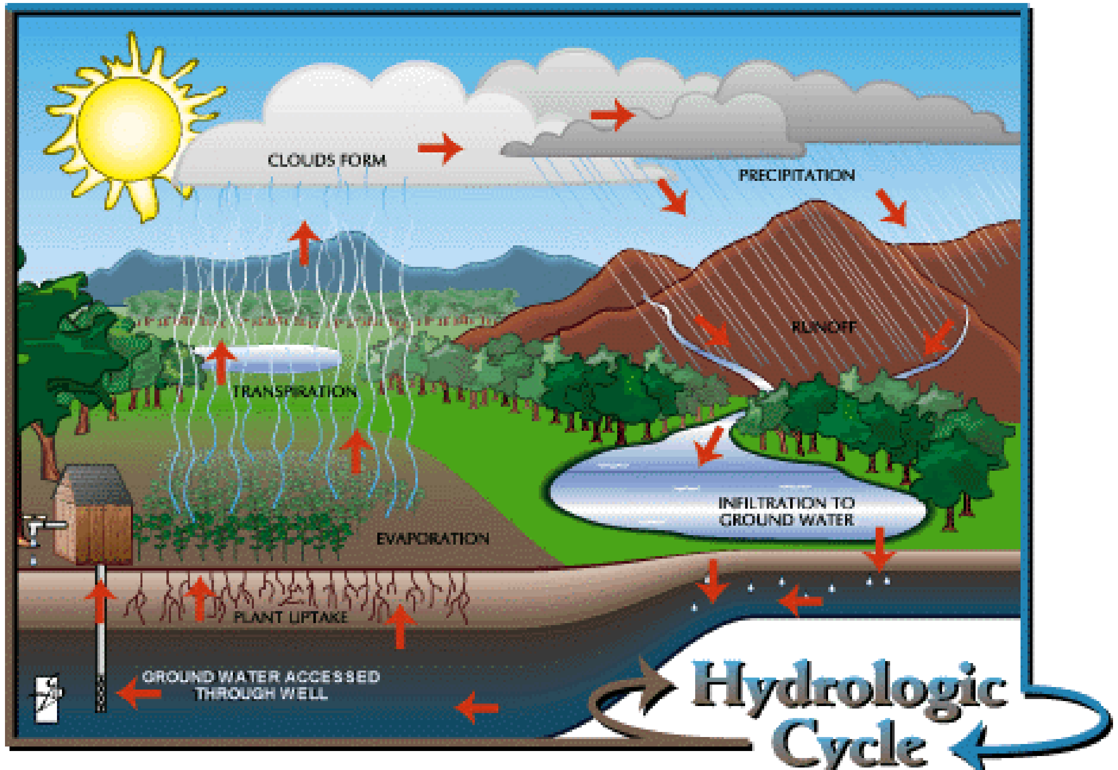
Global Water Resources

Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999.

105,000 km^3 or **0.0076%** of total water

Hydrologic Cycle

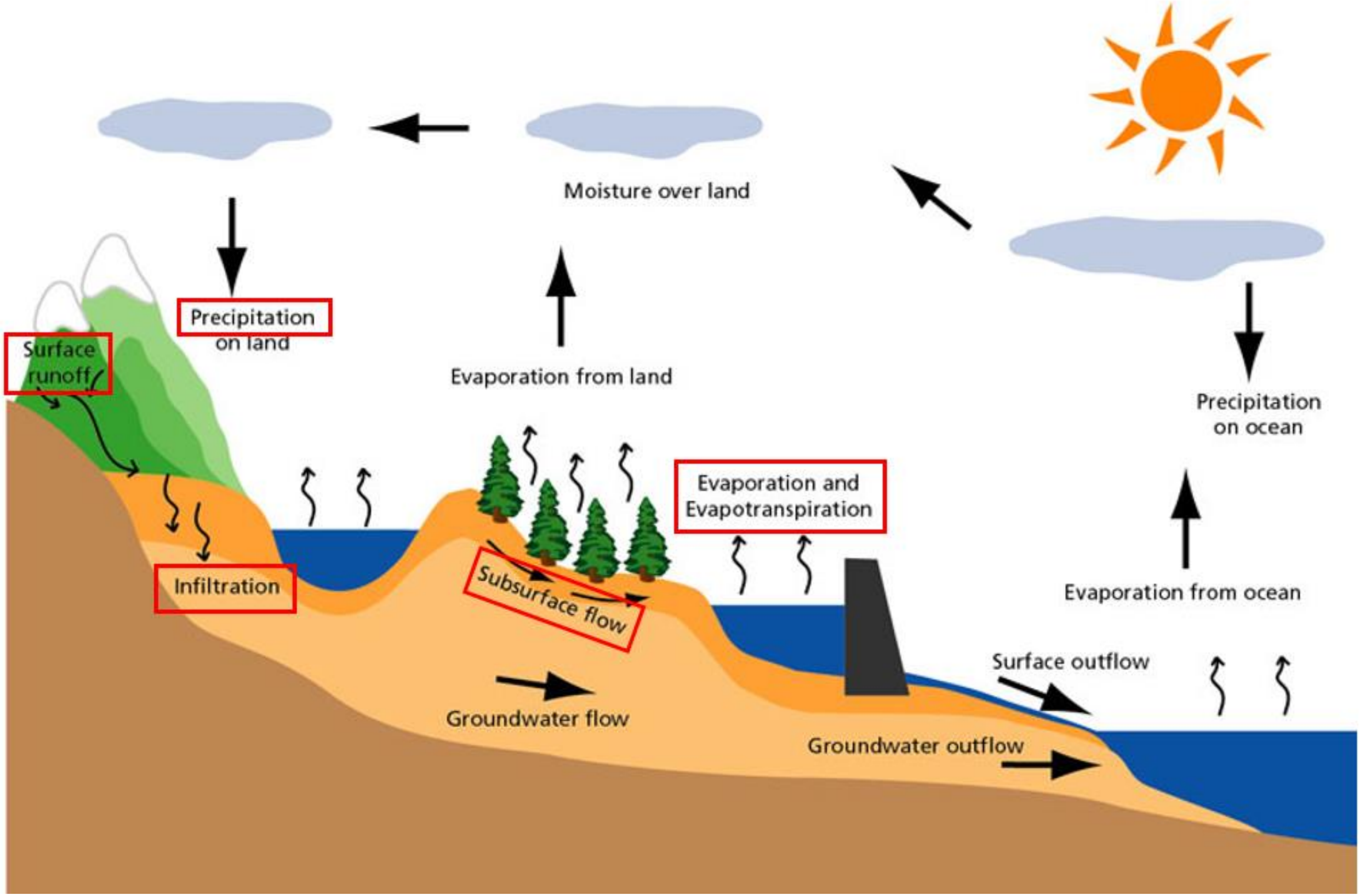
- Hydrologic cycle – A continuous process describes circulation of water in the environment.
- Through hydrologic cycle, water is transported from the oceans to the atmosphere to the land and back to the sea.



Components of hydrologic cycle

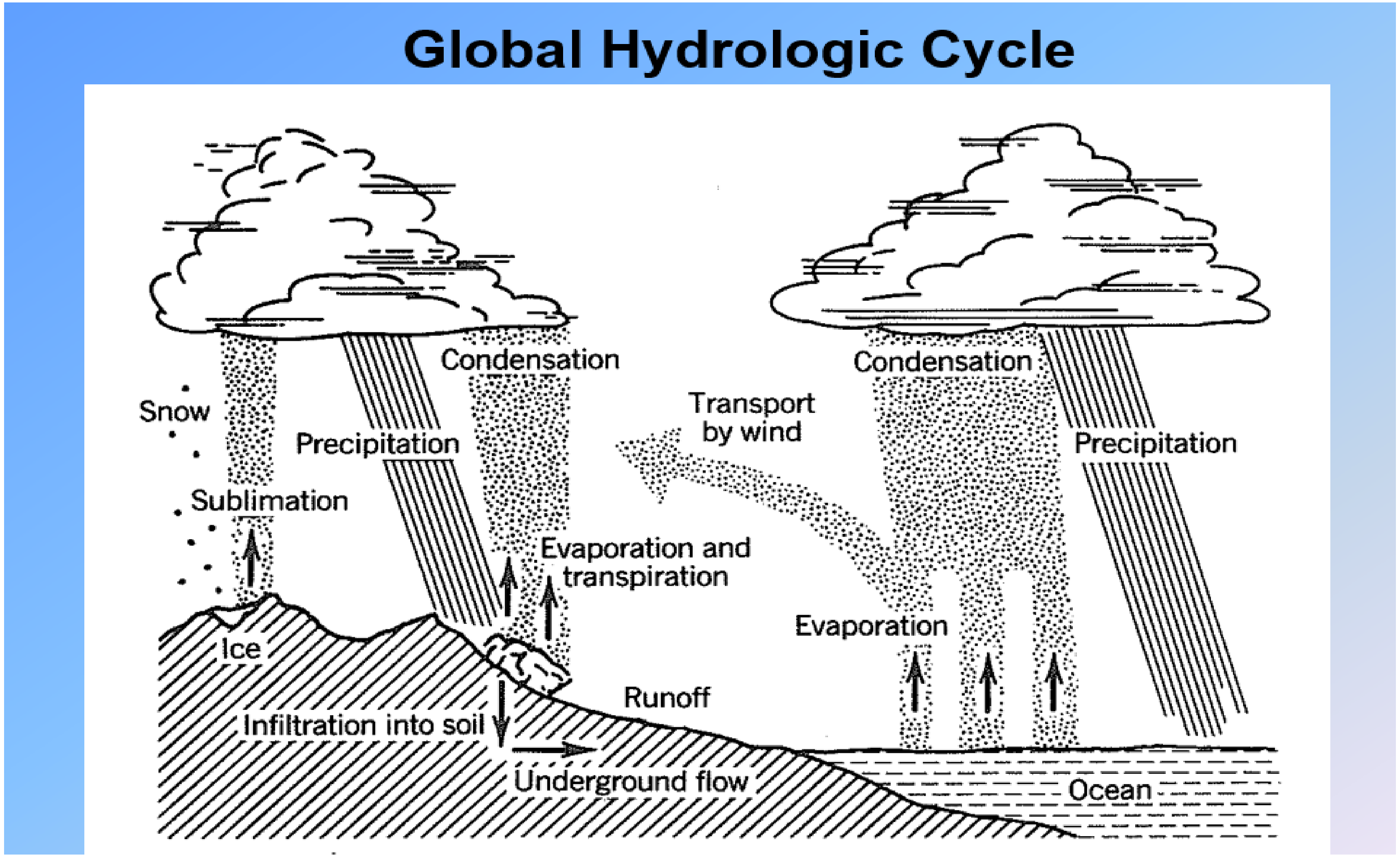
- Precipitation (P).
- Transpiration (T).
- Evaporation (E).
- Evapotranspiration (ET).
- Surface runoff (R).
- Groundwater flow (G).
- Infiltration (I)

Hydrologic Cycle

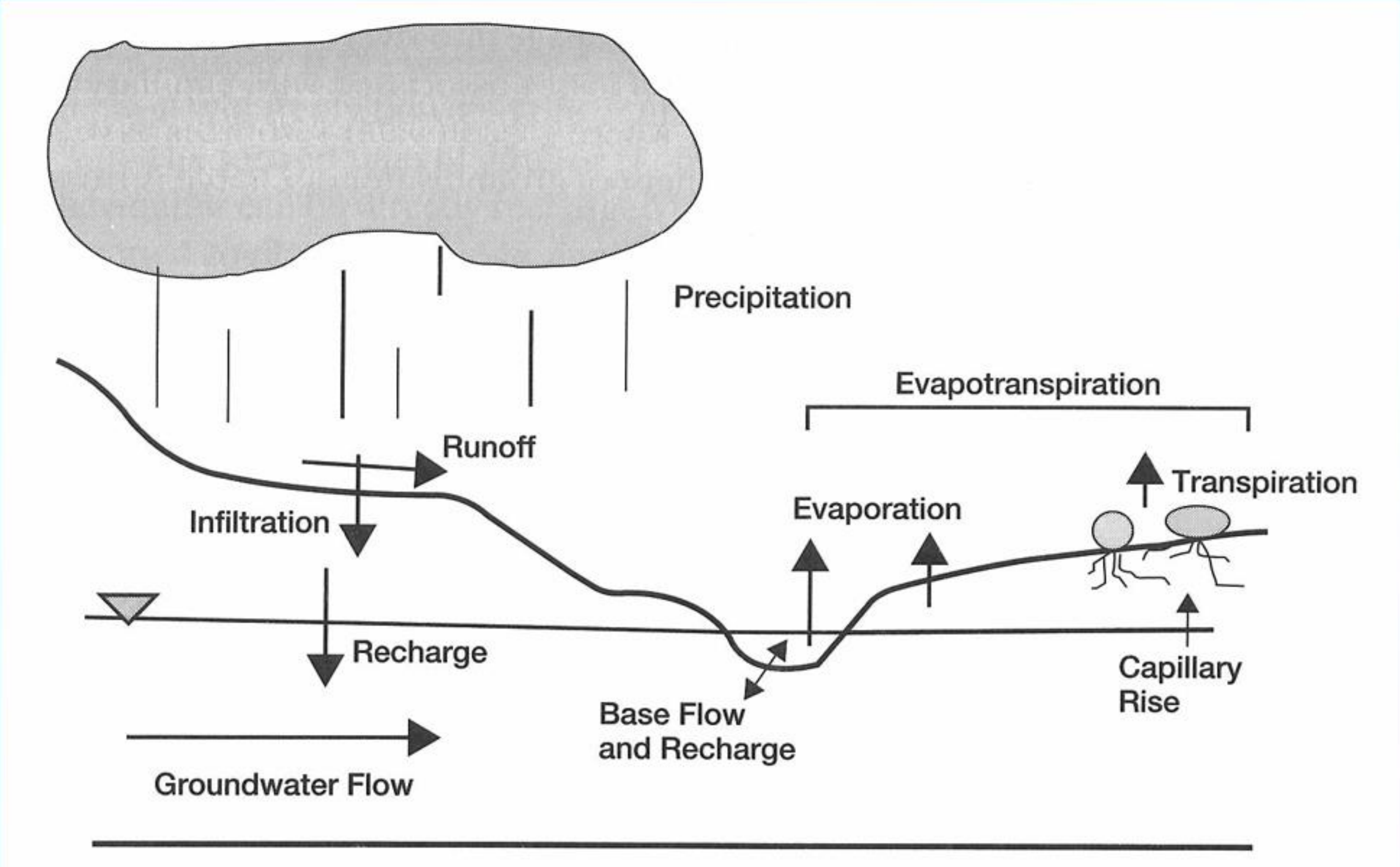


Hydrologic Cycle- Cont.

- World water problems require studies on regional, national, international, continental, and global scales.



Basin Hydrologic Cycle



Water Balance

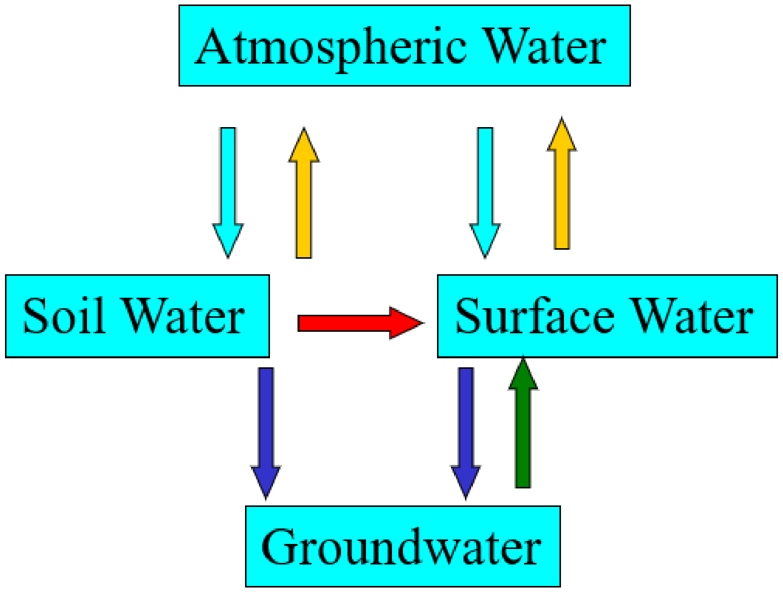
- A water balance can be established for any area of earth's surface by calculating the total precipitation input and the total of various outputs.
- The water-balance approach allows an examination of the hydrologic cycle for any period of time.
- The purpose of the water balance is to describe the various ways in which the water supply is expended.

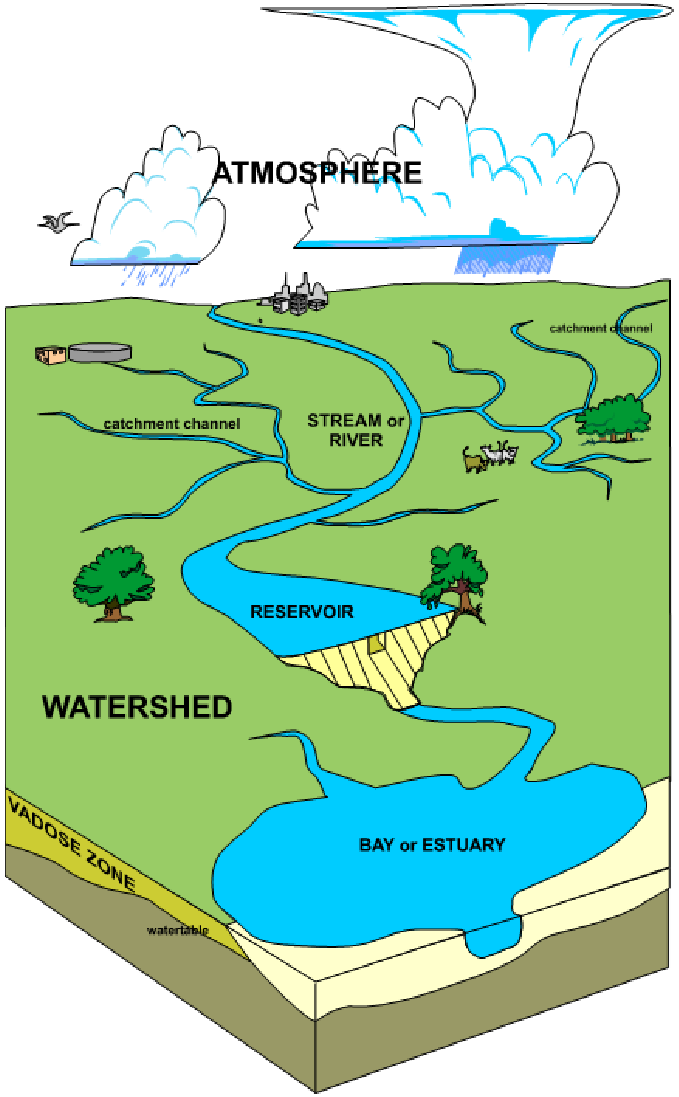
Water Balance- Cont.

- The water balance is defined by the general hydrologic equation, which is basically a statement of the law of conservation of mass as applied to the hydrologic cycle. In its simplest form, this equation reads
- The water balance defines the conservation of mass across the different compartments of the hydrological cycle (atmosphere, water bodies, soil and ground, vegetation, snowpack and ice, …)

Inflow = Outflow + Change in Storage

Water Balance

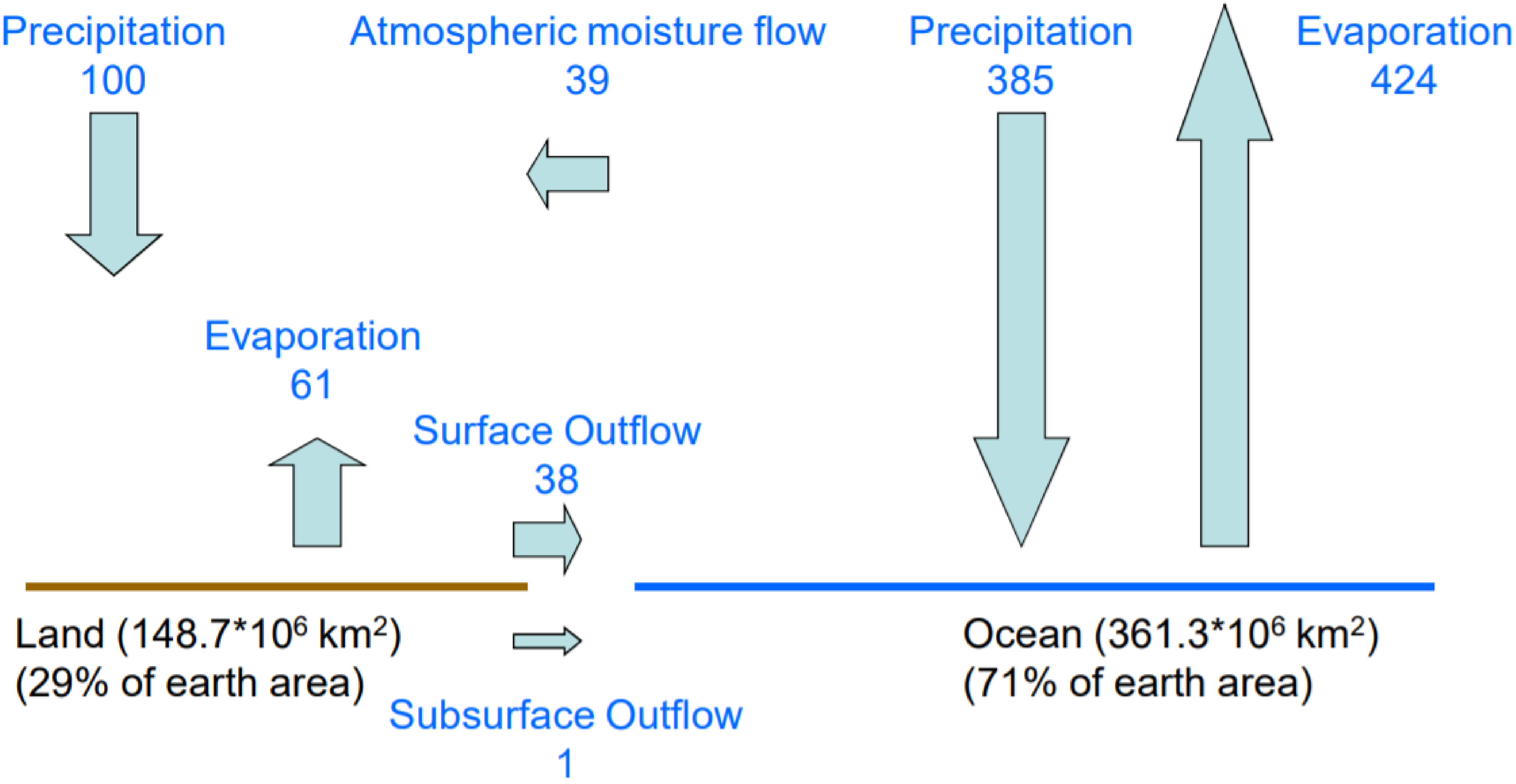




Inflow – Outflow = Change of Storage

$$I - Q = \frac{dS}{dt}$$

Global Water Balance (Volumetric)



Units are in volume per year relative to precipitation on land (119,000 km^3/yr) which is 100 units

Example

- If a vertical-walled reservoir having a surface area of 1 mi^2 receives an inflow of 12 cfs, how long will it take to raise the reservoir level by 6 inches?

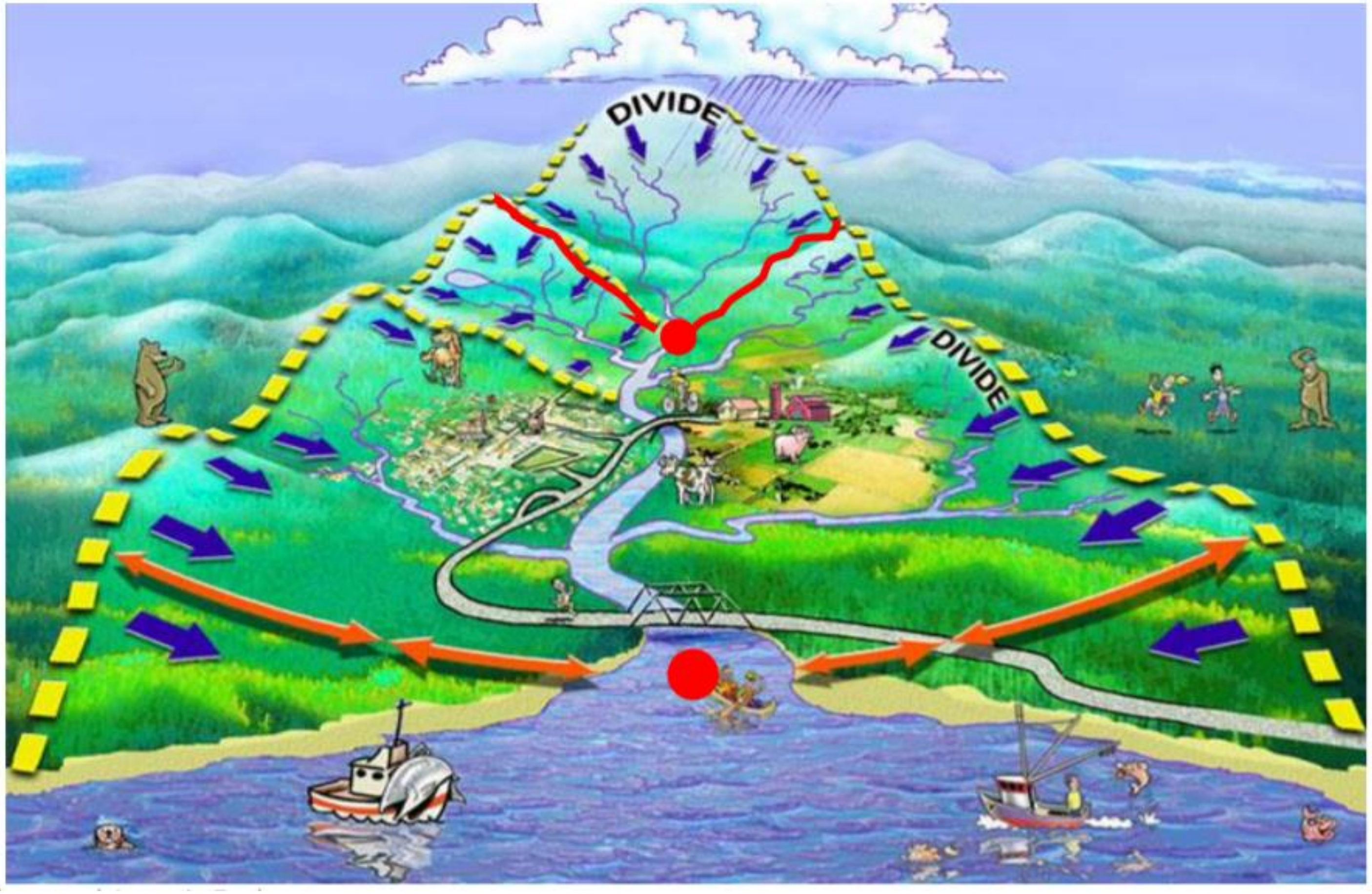
1 mi = 5280 ft

Example

- If the mean annual runoff of a drainage basin of 10000 km^2 is 140 m^3/sec, and the average annual precipitation is 105 cm, estimate the ET losses for the area in 1 year. What are your assumptions? How reliable do you think this estimate is?

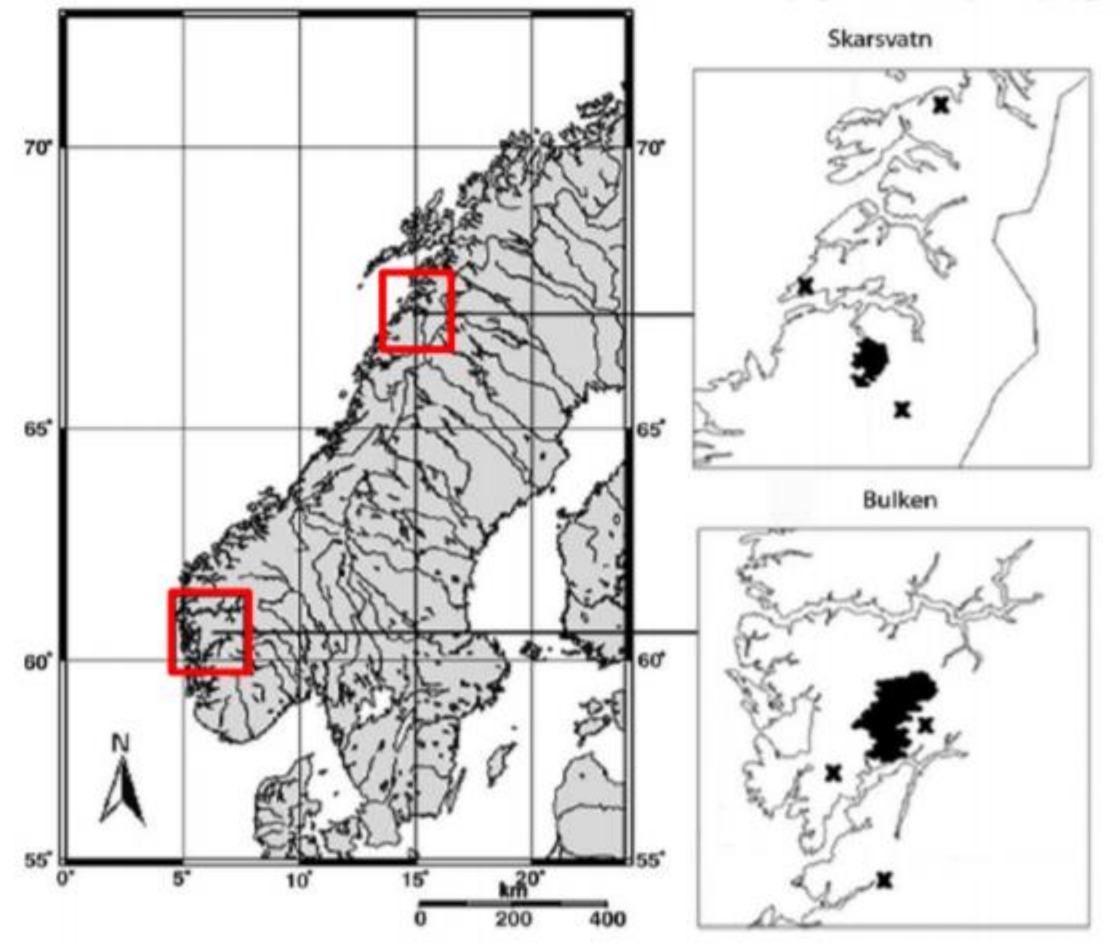
A **catchment** is an **area** in which water falling on or flowing across the land surface drains into a particular stream or river and flows ultimately through a single point or outlet.

Catchment area is defined by topographical water divide.



Watershed divide

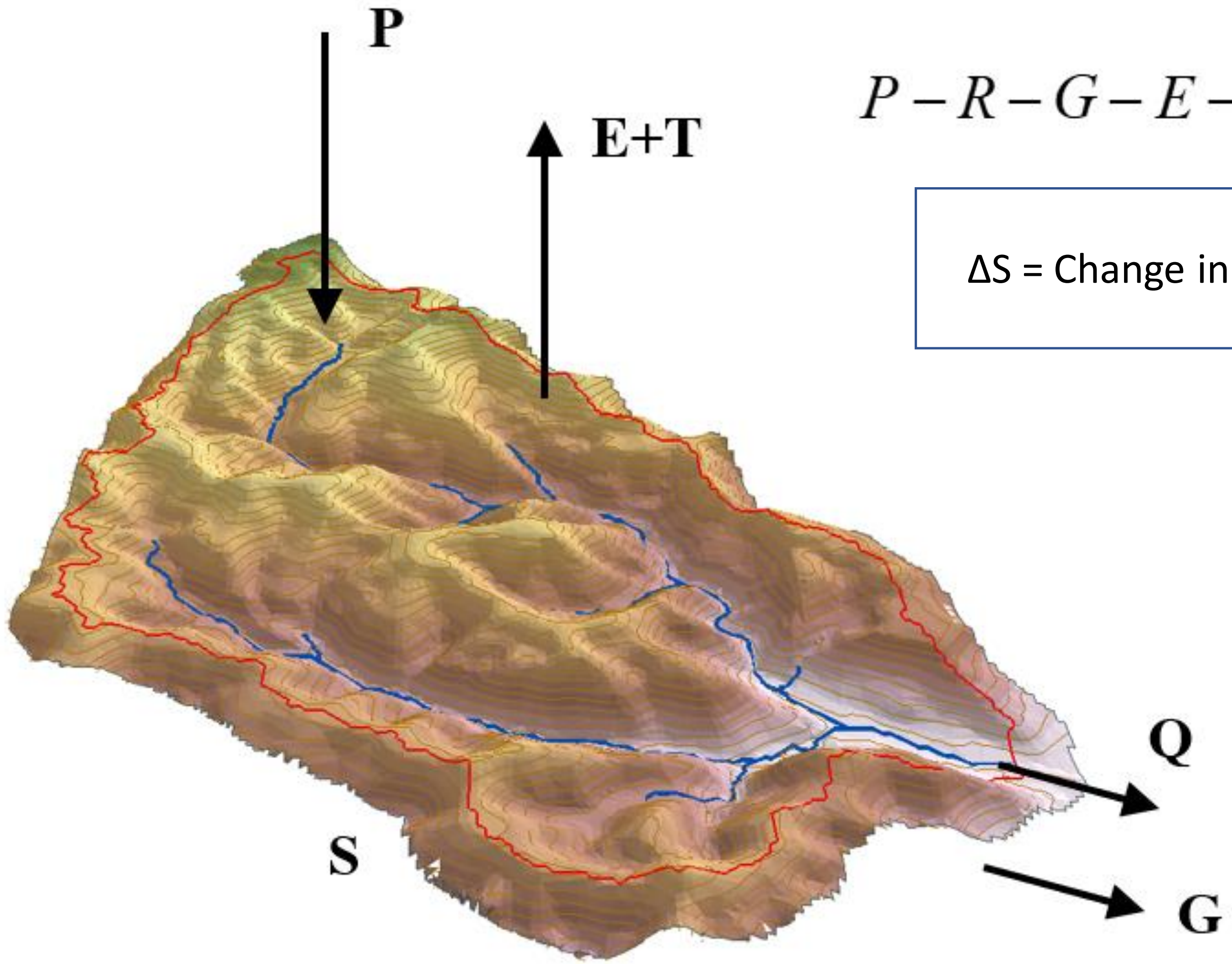
A watershed starts at the highest points on the landscape, like mountain peaks and ridgelines that divide one valley or drainage from another. The imaginary line that connects those high points is called the watershed divide.



Skarsvatn 86 km2 – Bulken 1094 km2

Amazon 7 x 10^6 km^2

Watershed water balance

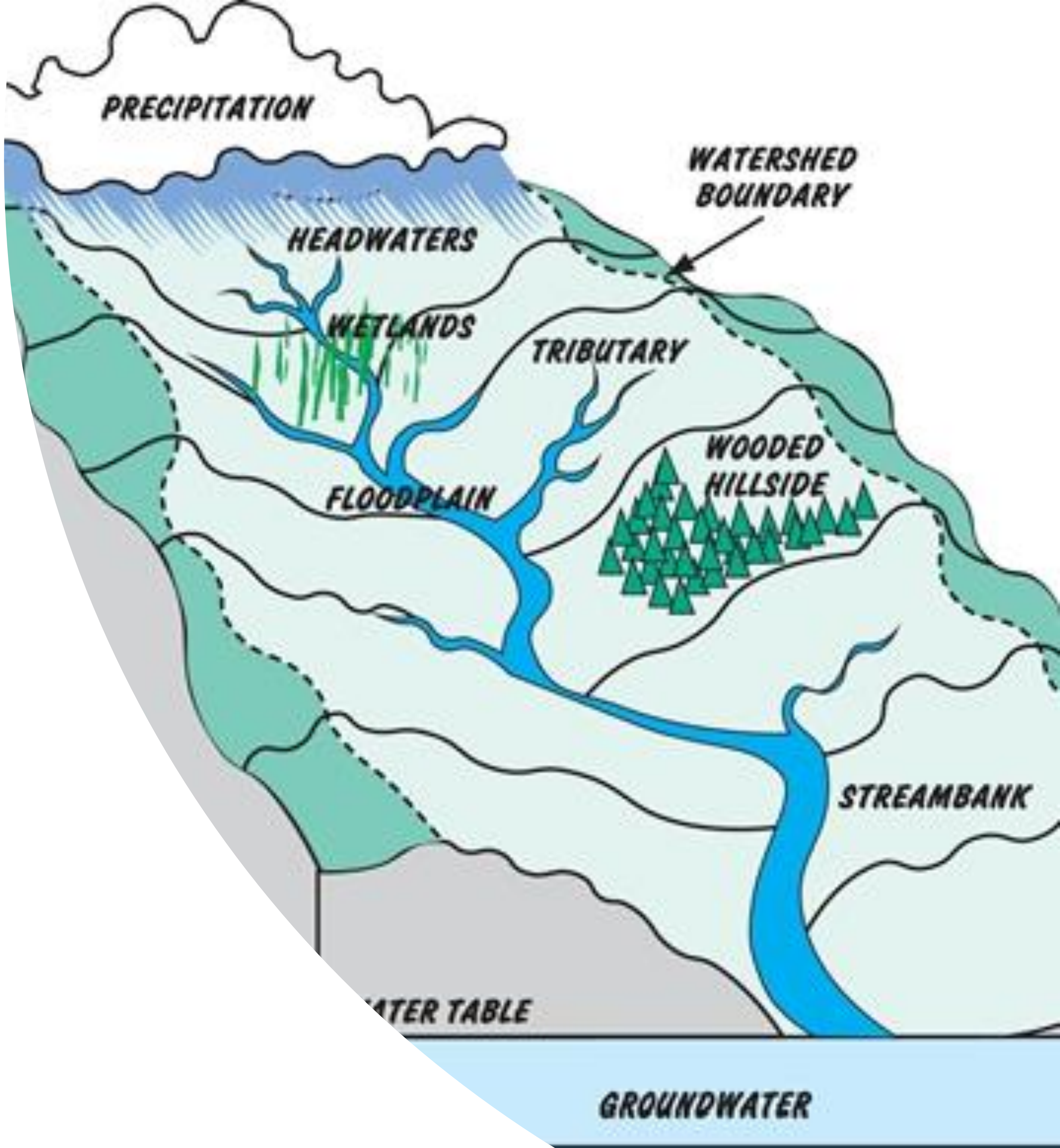


$$P - R - G - E - T = \Delta S$$

ΔS = Change in water storage

Cont. Watershed

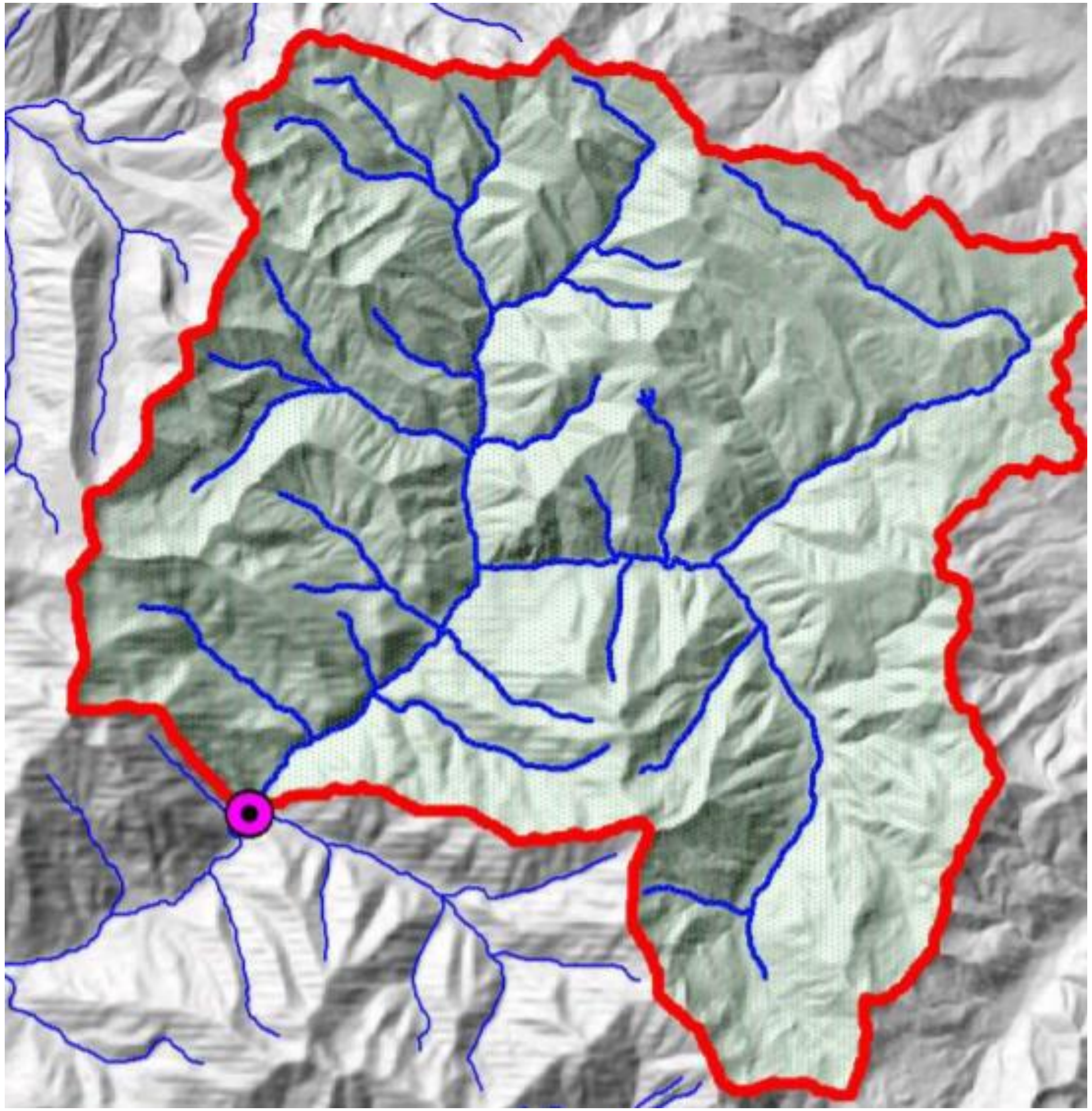
- Watershed is the basic unit of all hydrologic analysis and designs.
- Usually a watershed is defined for a given drainage point. This point is usually the location at which the analysis is being made and is referred to as the watershed “outlet”.
- The watershed, therefore, consists of all the land area that drains water to the outlet during a rainstorm.

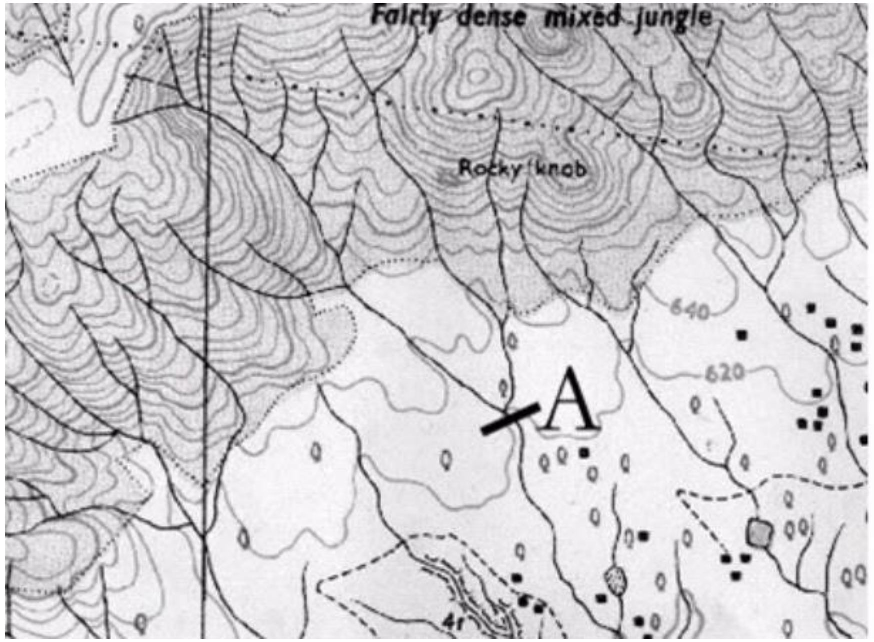


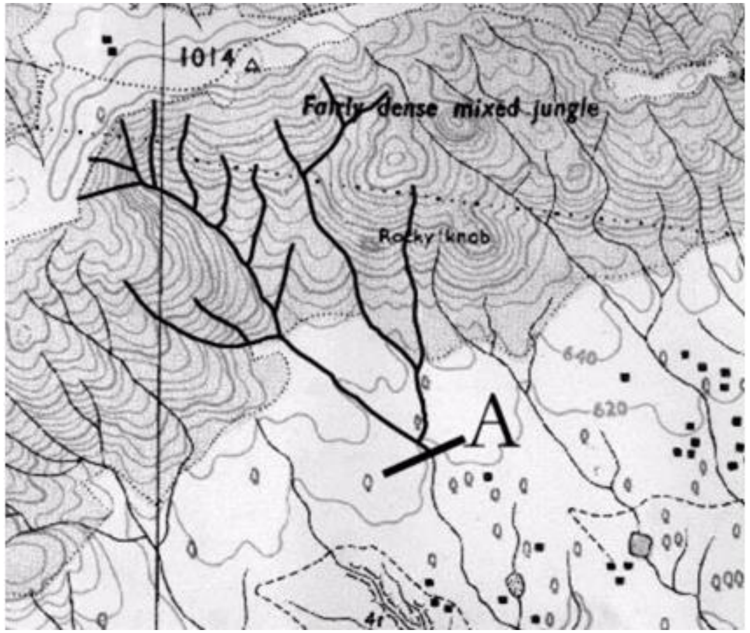
Watershed delineation

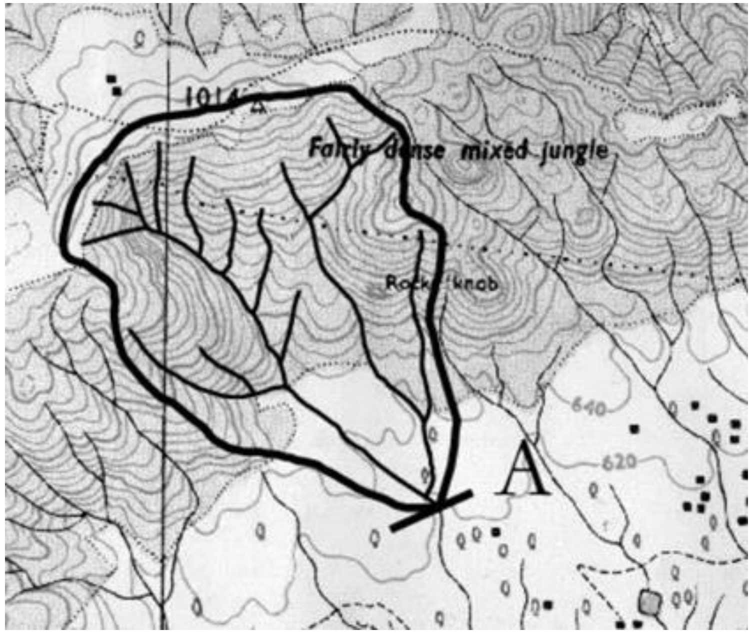
- Creating a boundary that represents the contributing area for a particular control point or outlet.

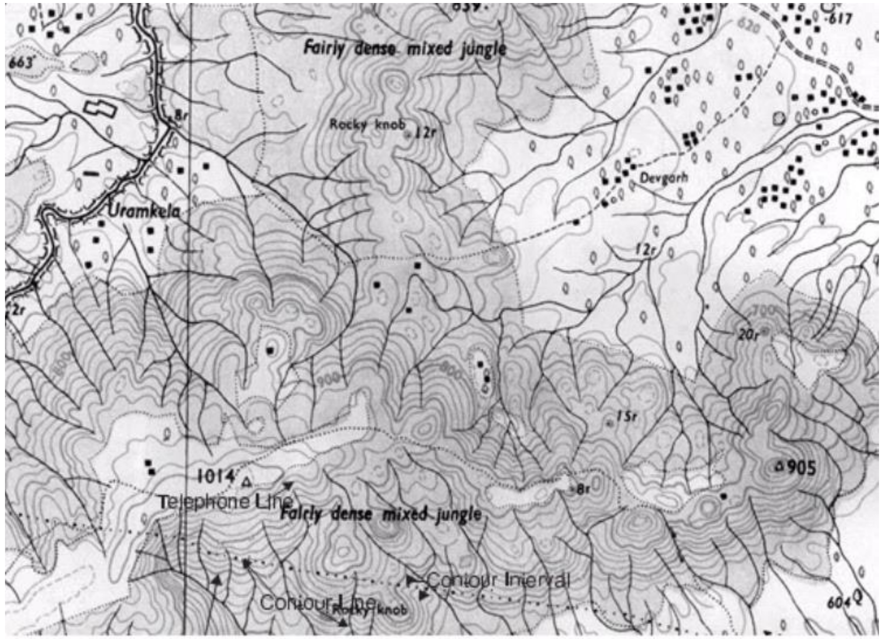
- Used to define boundaries of the study area, and/or to divide the study area into sub-areas.











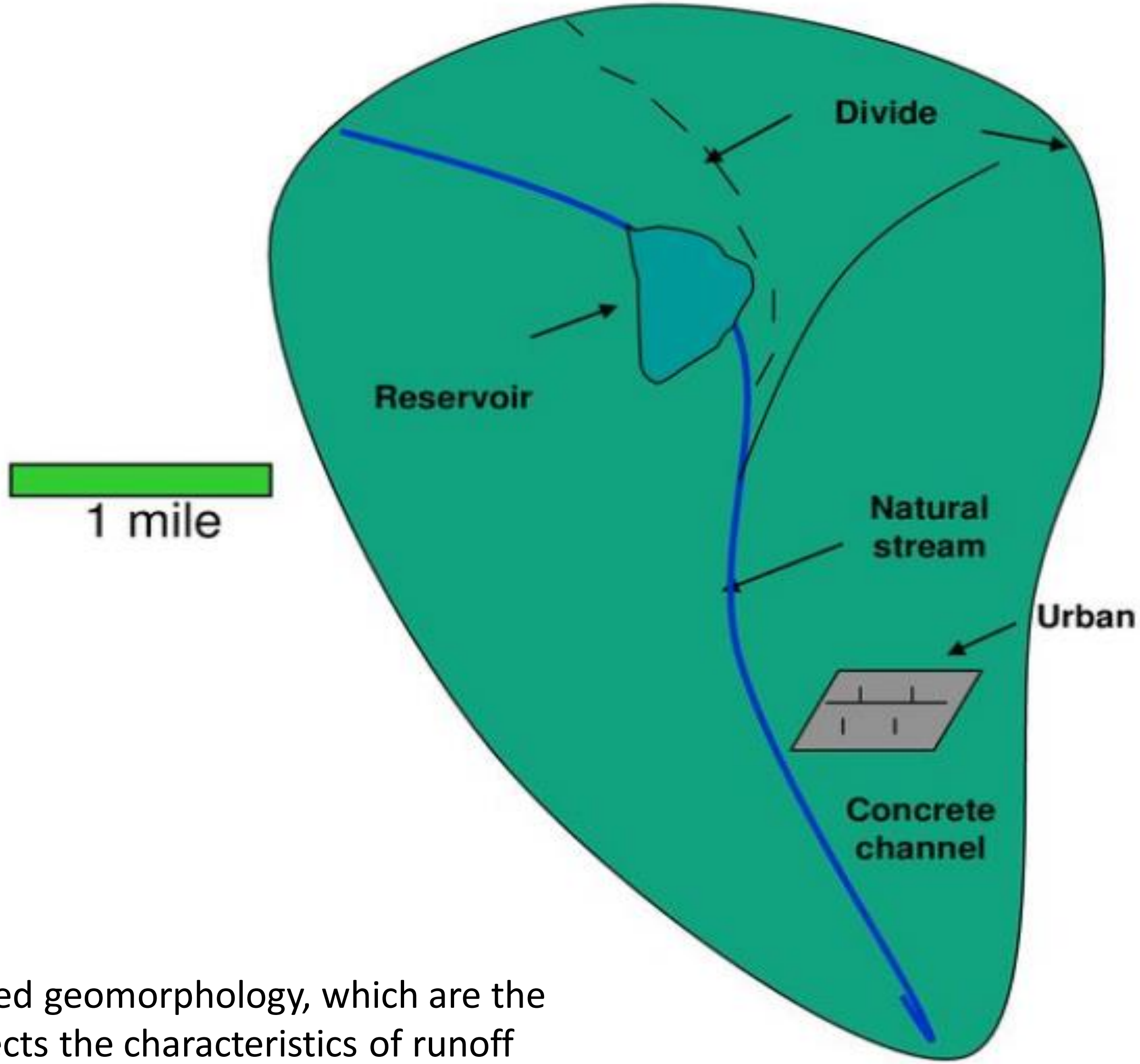
Watershed delineation steps

Cont. Watershed delineation

- Use a topographic map(s) to locate the river, lake, stream, wetland, or other waterbodies of interest.
- Identify the point with respect to which the watershed is to be marked(the exit point or outlet).
- Trace the watercourse from its source to its mouth, including the tributaries. Mark the drainage lines.
- Check the slope of the landscape by locating two adjacent contour lines and determine their respective elevations. The slope is calculated as the change in elevation, along a straight line, divided by the distance between the endpoints of that line.
- Watershed boundaries will be marked finally.

Watershed Characteristics

- Size
- Slope
- Shape
- Soil type
- Storage capacity

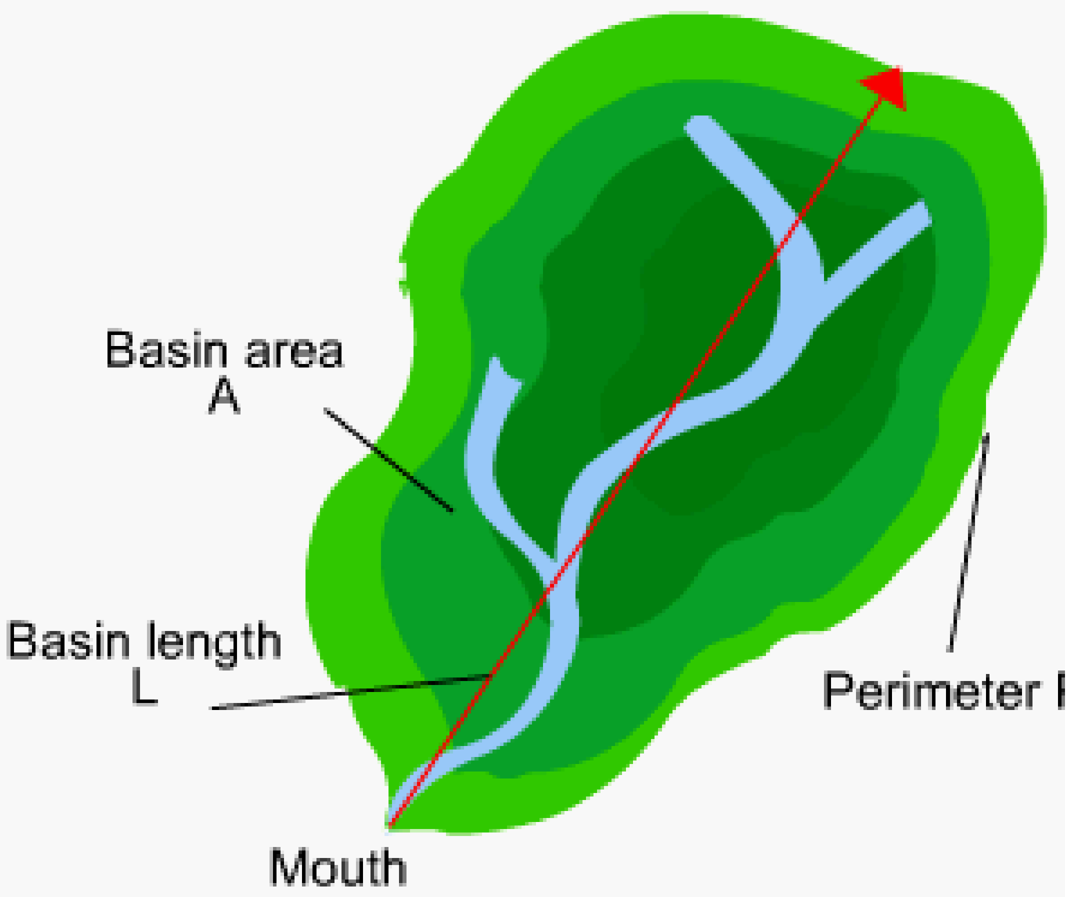


Watershed characteristics are referred to as watershed geomorphology, which are the physical properties of watersheds. It significantly affects the characteristics of runoff and hydrological responses such as the flow regime during floods and periods of drought.

Drainage Area

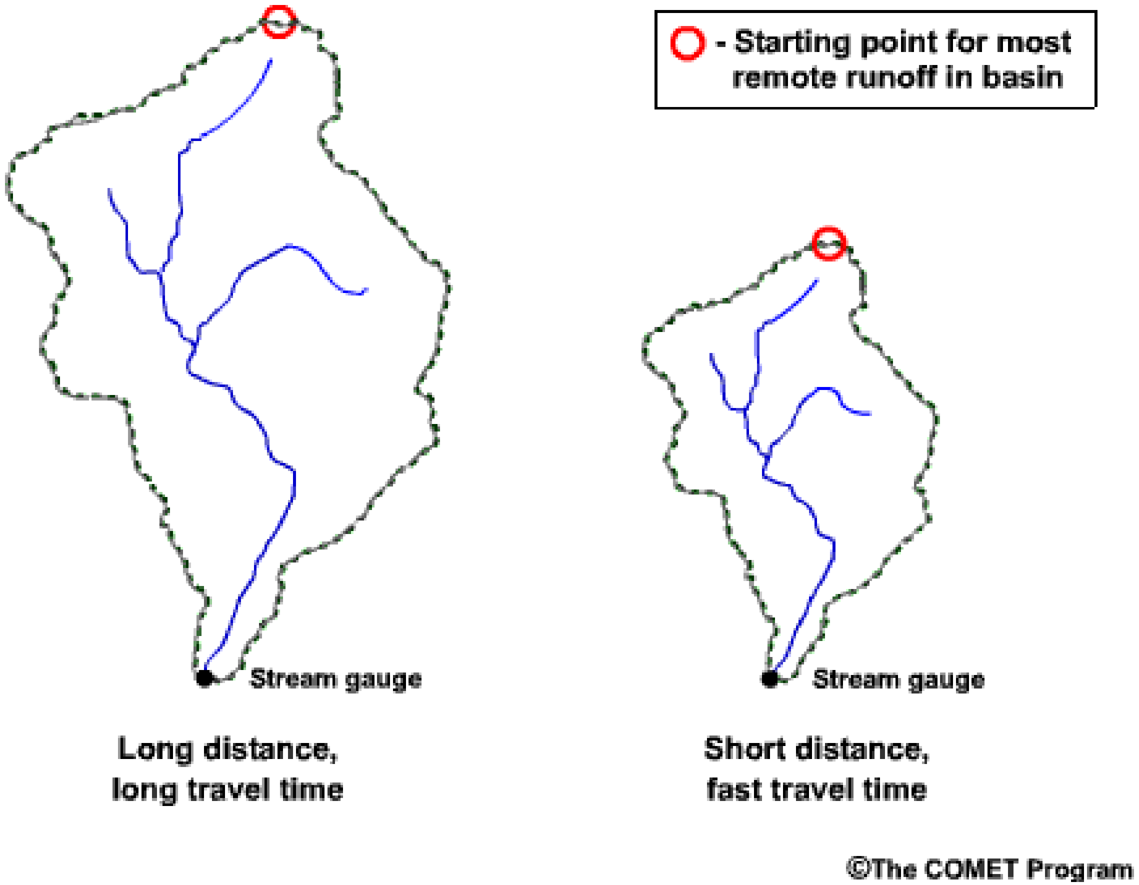
- The drainage area (A) is the probably the single most important watershed characteristic for hydrologic design. It reflects the volume of water that can be generated from rainfall.

- It is common in hydrologic design to assume a constant depth of rainfall occurring uniformly over the watershed. Under this assumption, the volume of water available for runoff would be the product of rainfall depth and the drainage area. Thus the drainage area is required as input to models ranging from simple linear prediction equations to complex computer models



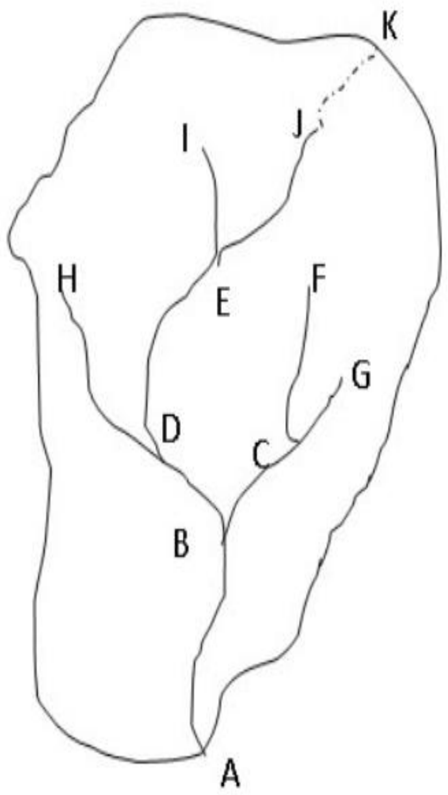
Watershed length

- The length (L) of a watershed is the second watershed characteristic of interest. While the length increases as the drainage increases, the length of a watershed is important in hydrologic computations. Watershed length is usually defined as the distance measured along the main channel from the watershed outlet to the basin divide.



Example 1- Main channel passes through points A, B, D, E and J. The length of AB is 1.8 km, BD is 1.3 km, DE is 1.7 km and EJ is 1.8 km. The remotest point of the watershed is K which is 0.8 km far from the start of main channel, i.e., point J. What will be the watershed length?

Solution:



The length of main channel is

AB+BD+DE+EJ = 1.8+1.3+1.7+1.8 = 6.6 km

The distance between the start of main channel and remotest point (shown by dotted line in the picture) is JK

Length of JK is 0.8

Hence total length of watershed is 6.6+0.8 = 7.4 km

Watershed Slope

- Watershed slope reflects the rate of change of elevation with respect to distance along the principal flow path. Typically, the principal flow path is delineated, and the watershed slope (S) is computed as the difference in elevation (ΔE) between the end points of the principal flow path divided by the hydrologic length of the flow path (L):

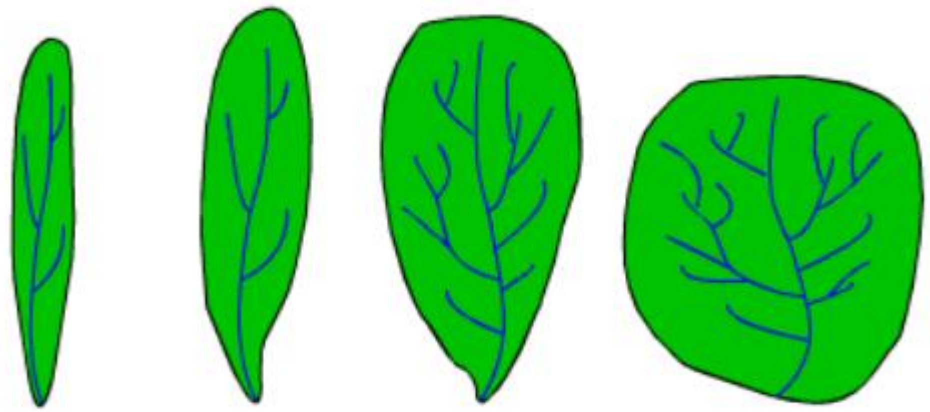
$$S = \Delta E/L$$

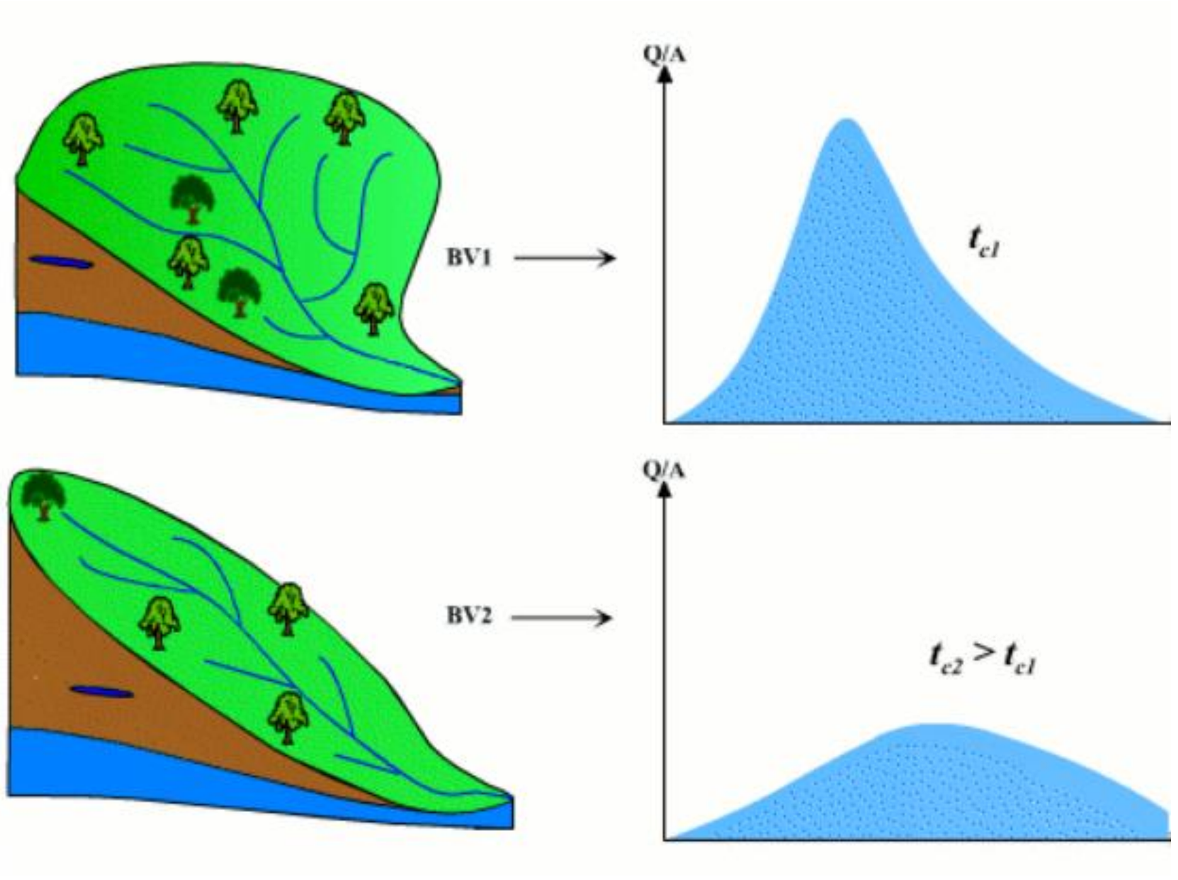
Example -2 . In continuation of example 1: K, A and J is having elevations of 578m, 316 m, 532 m respectively. Calculate the watershed slope.

Watershed slope = elevation difference between point K and A divided by watershed length i.e. (578-316)/7.4 = 262/7.4 = 35.4 m per km = 3.54%

Watershed shape

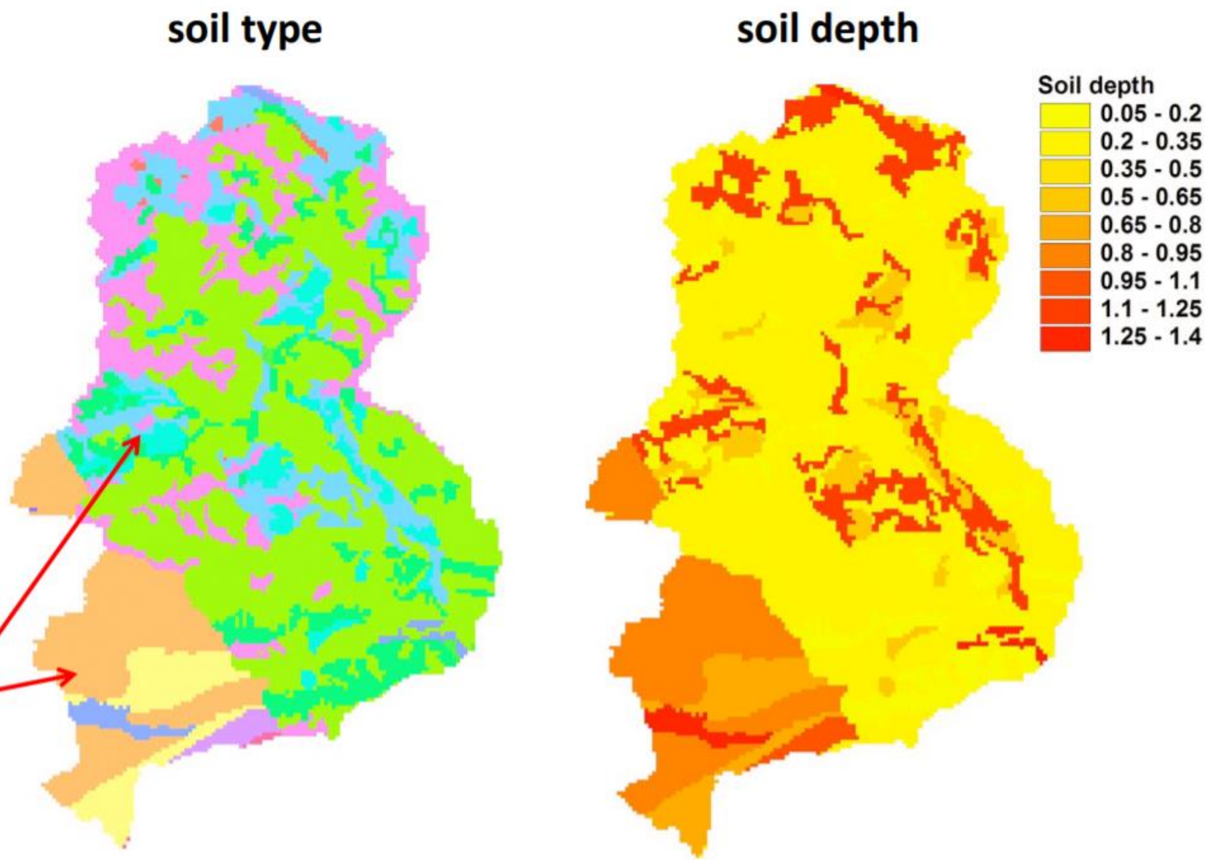
- The shape of a watershed influences the shape of its characteristic hydrograph. For example, a long shape watershed generates, for the same rainfall, a lower outlet flow, as the concentration time is higher. A watershed having a fan-shape presents a lower concentration time, and it generates higher flow.





Soil Type

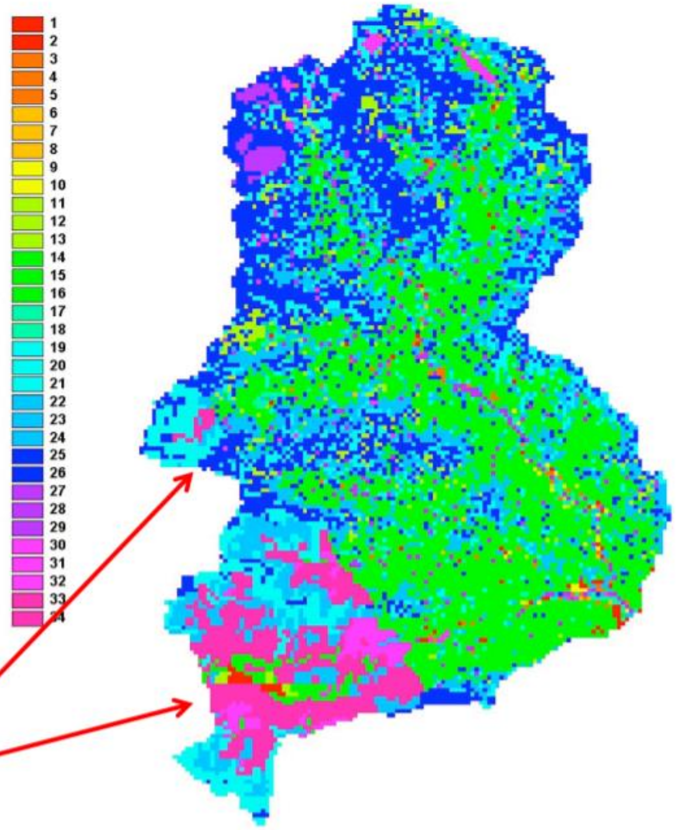
- use
  - ↳ *delineation of infiltration and soil storage characteristics*
  - ↳ *parameterisation of infiltration models*
- problems
  - ↳ *accuracy of information*
  - ↳ *different classification / resolution used by different countries*



(Maggia river basin, Tessin, CH)

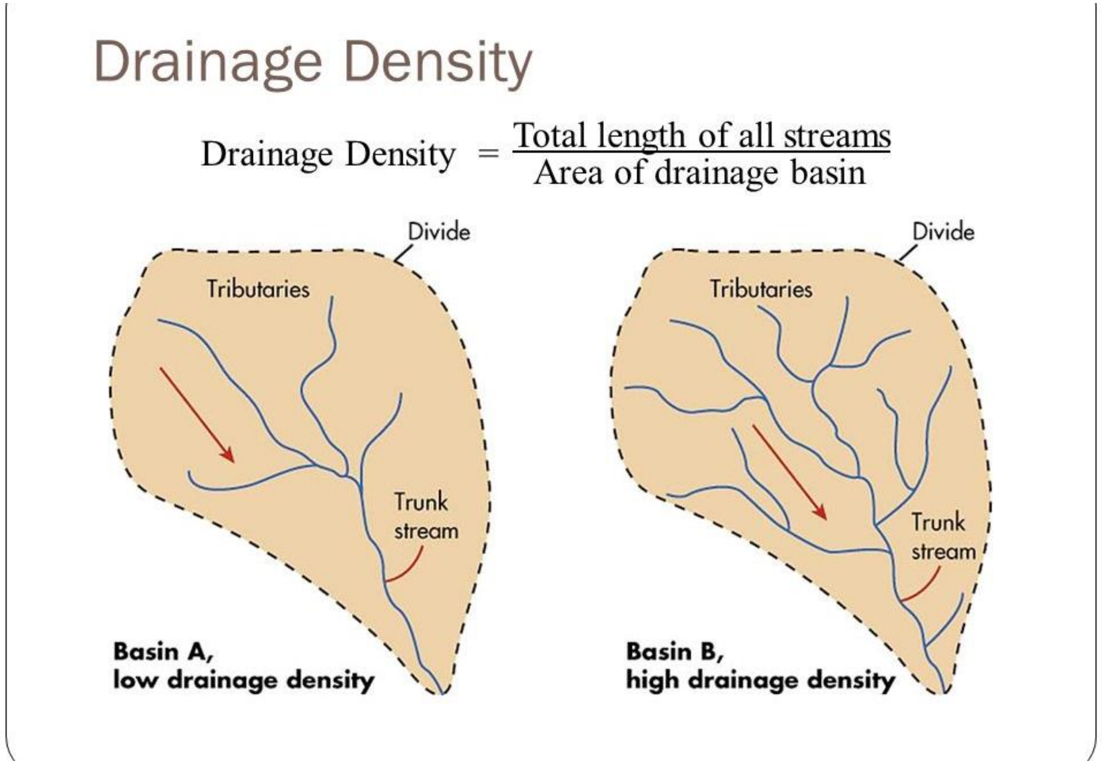
Land Use

- use
  - ↳ ***parameterisation of models***
    - – ***infiltration*** (e.g. SCS-CN)
    - – ***evapotranspiration***
- problems
  - ↳ ***representativeness of map depends on raster size***
  - ↳ ***different classification /resolution used by different countries***



1	Continuos urban fabric
2	Discontinuous urban fabric
3	Industrial or commercial units
4	Road and railway networks and associated land
5	Mineral extraction sites
6	Construction sites
7	Green urban areas
8	Sport & leisure facilities, Gras landingstrip
9	Non-irrigated arable
10	Vineyards
11	Fruit trees and berry plantations
12	Pastures
13	Complex cultivation pattern
14	Principals crops with significant natural vegetation
15	Forest
16	Open Forest
17	Meadows and agricultural land, good condition
18	Meadows and agricultural land, poor condition
19	Meadows in mountains
20	Natural grassland
21	Moors and heathland
22	Bushy sclerophillous vegetation
23	Transitional woodland-scrub
24	Sand plains
25	Bare rock
26	Sparsely vegetated areas
27	Glaciers and perpetual snow
28	Inland marshes (wet areas)
29	Water courses
30	Water bodies
31	Littoral zones
32	Broad Leaf
33	Coniferous Forest
34	Mixed Forest

Drainage density



- Drainage density is the total length of all the streams and rivers in a drainage basin divided by the total area of the drainage basin. It is a measure of how well or how poorly a watershed is drained by stream channels.

Cont. Drainage density

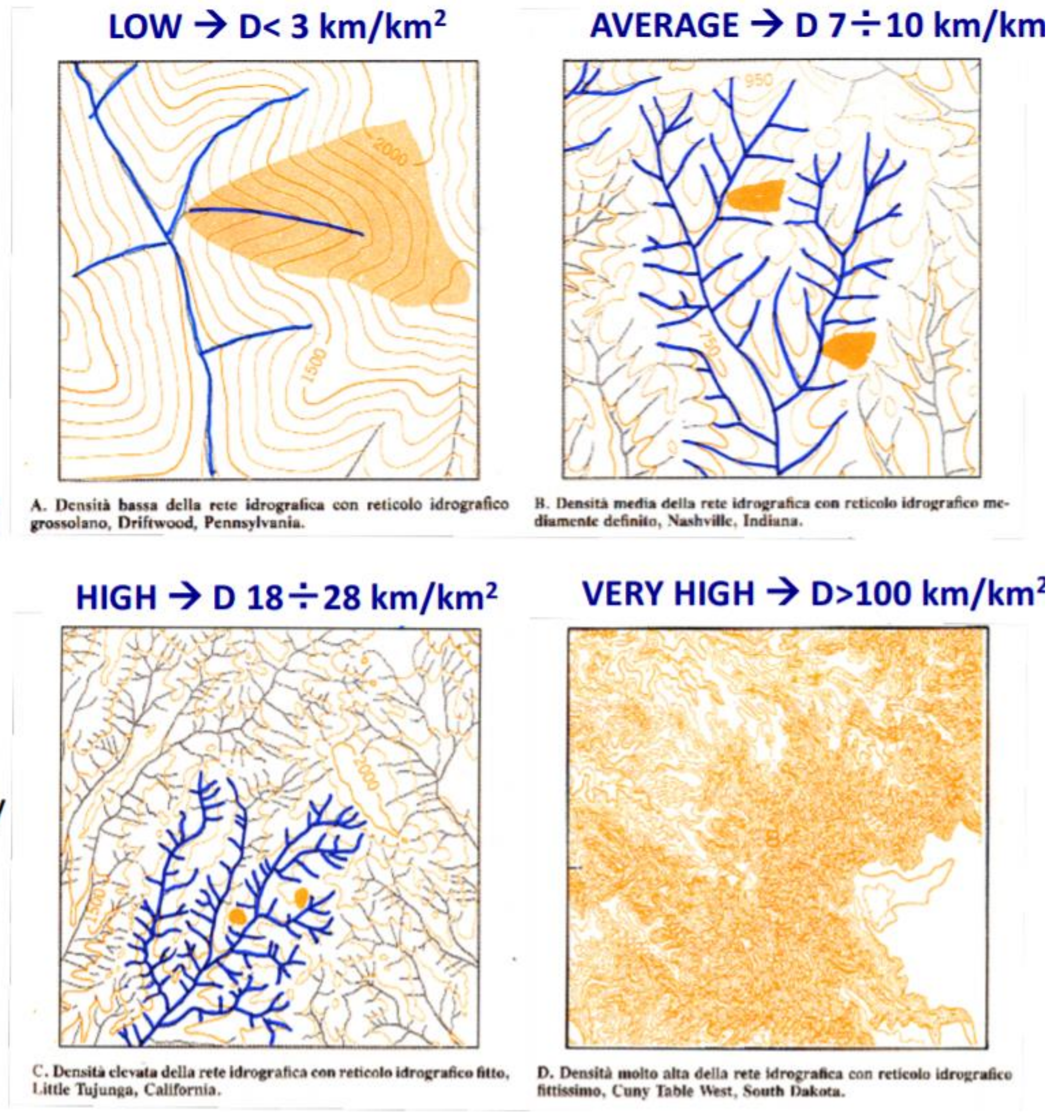
- It measures the efficiency of the basin drainage (i.e. of how well or how poorly a watershed is drained by rivers).

- It depends upon both climate (e.g. rainfall regime) and physical characteristics (e.g. geology, slope, soil, land cover) of the drainage basin.

- For equal climatic characteristics can be used as proxy information for permeability

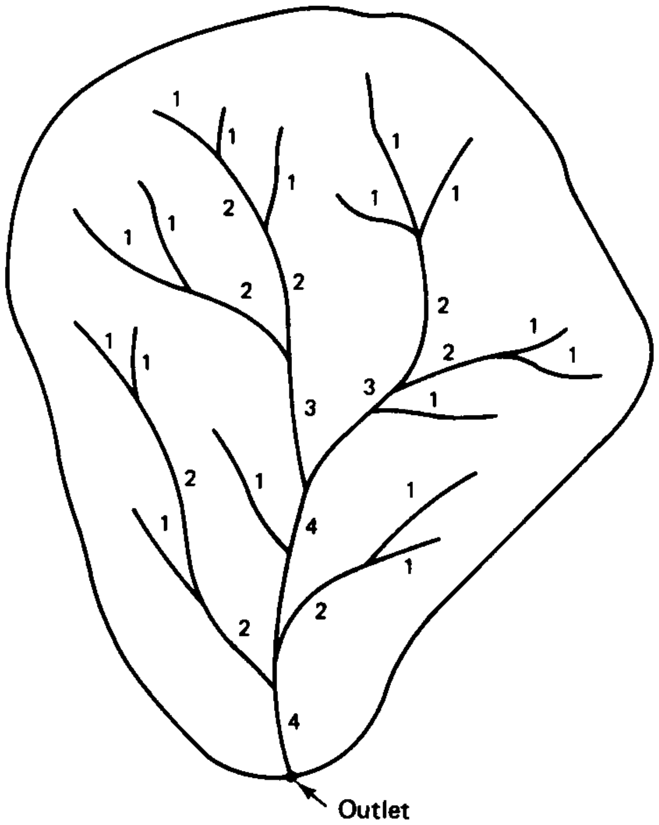
↳ *high D → low permeability*

↳ *low D → high permeability*



Stream order and Hortons Law

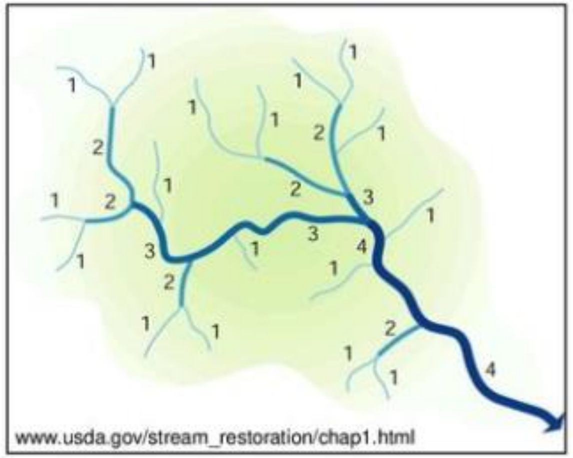
The stream order or waterbody order is a positive whole number used in geomorphology and hydrology to indicate the level of branching in a river system.



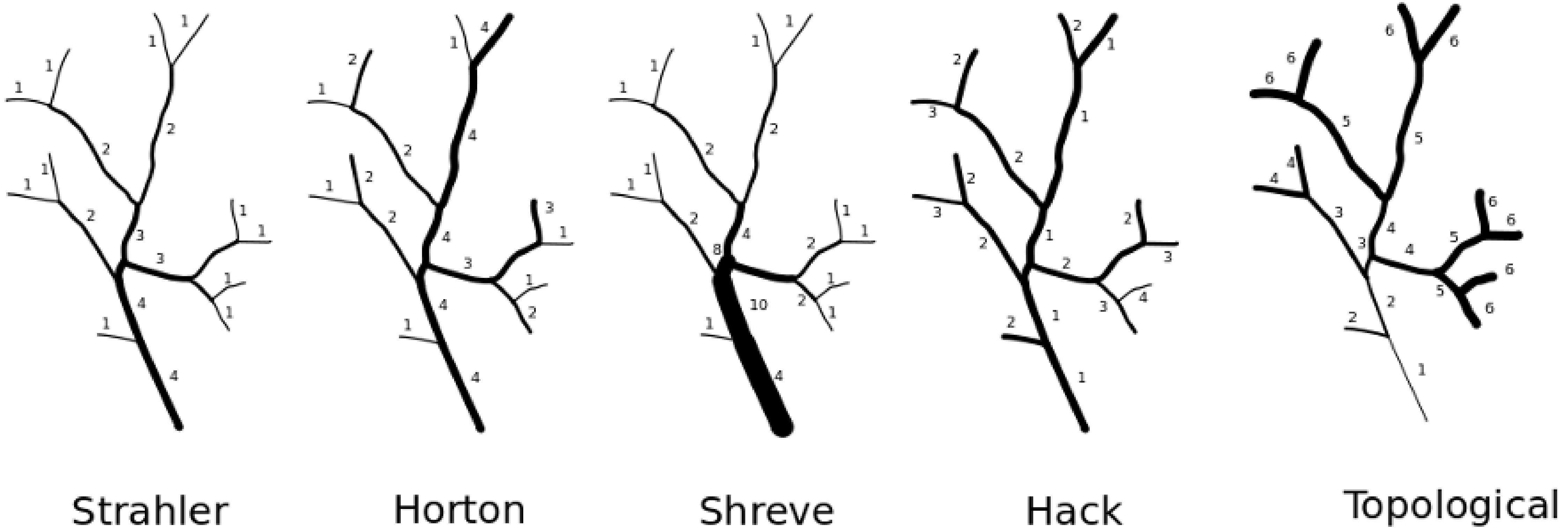
The **stream order** is a measure of the degree of stream branching within a watershed.

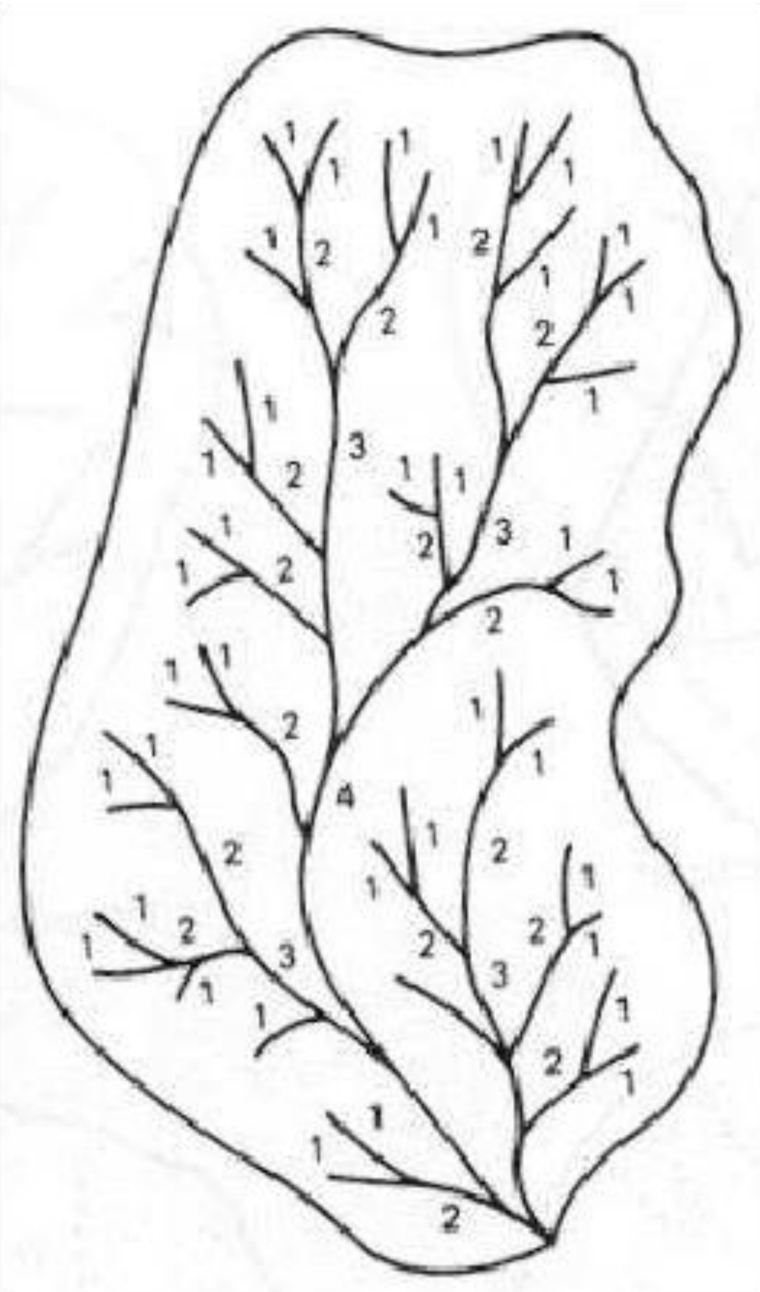
Cont. Stream order

- A method of classifying or ordering the hierarchy of natural channels.
- Strahler (1957) is the most widely used system.
- Stream order correlates well with drainage area, but is also regionally controlled by topography & geology.



Stream Order System

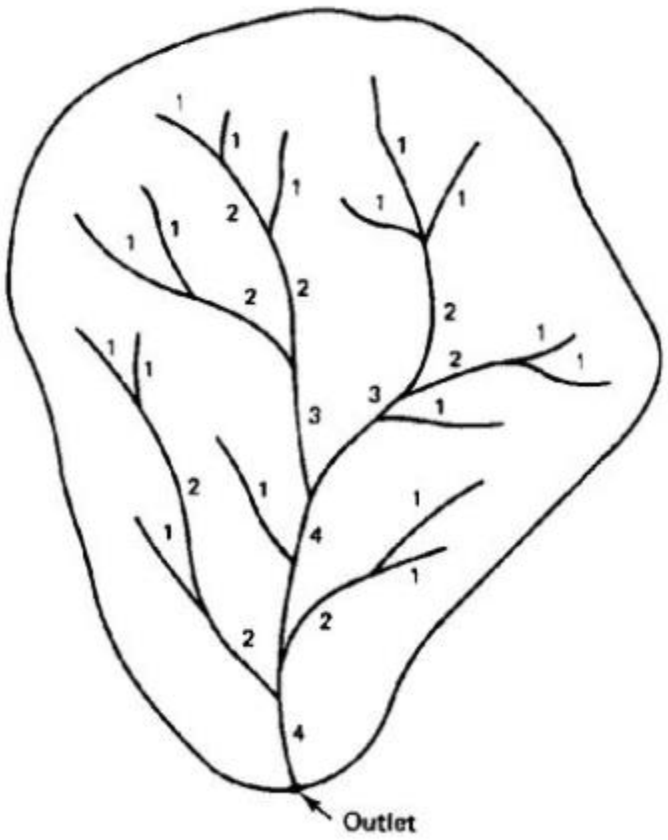




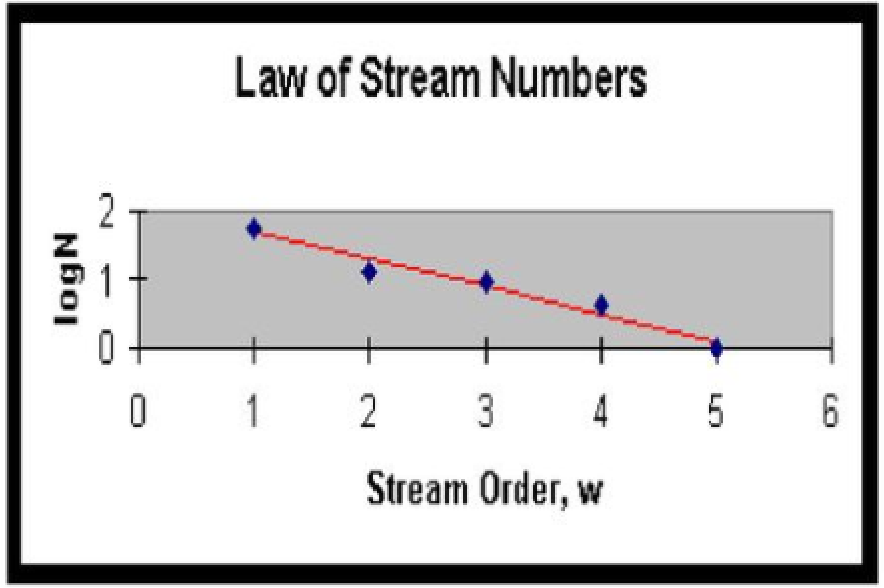
Cont. Stream order and Hortons Law

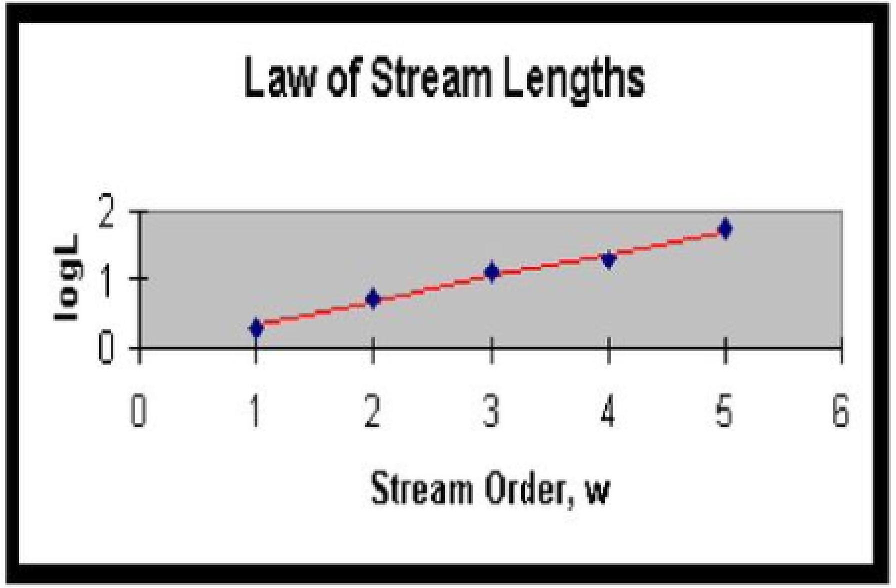
- Each length of stream is indicated by its order (for example, first-order, second-order, etc.). A first-order stream is an unbranched tributary, a second-order stream is a tributary formed by two or more first-order streams. A third-order stream is a tributary formed by two or more second-order streams and so on. In general, an nth order stream is a tributary formed by two or more streams of order (n-1) and streams of lower order.

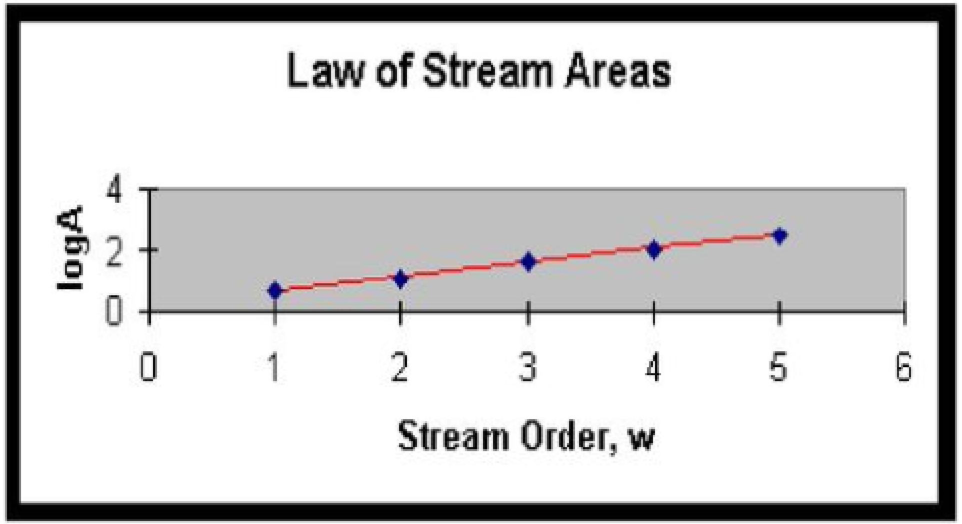
Horton's Law of Streams (modified by Strahler)



Law of Stream Lengths
Law of Stream Areas
Bifurcation Ratio


Law of Stream Numbers
logN
2
1
0
0 1 2 3 4 5 6
Stream Order, w


Law of Stream Lengths
logL
2
1
0
0 1 2 3 4 5 6
Stream Order, w


Law of Stream Areas
logA
4
2
0
0 1 2 3 4 5 6
Stream Order, w

Denoting by *m* the slopes of the corresponding fits

$$R_B = \frac{1}{anti\log(m)}$$

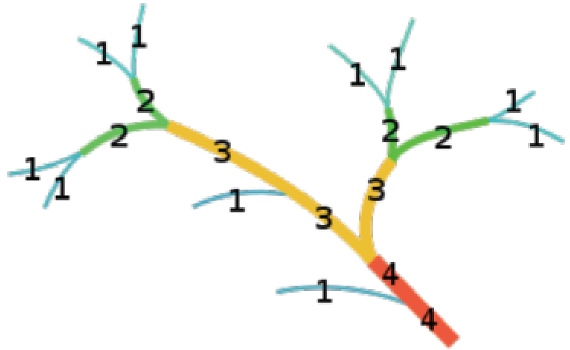
$$R_L = anti\log(m)$$

$$R_A = anti\log(m)$$

Bifurcation Ratio

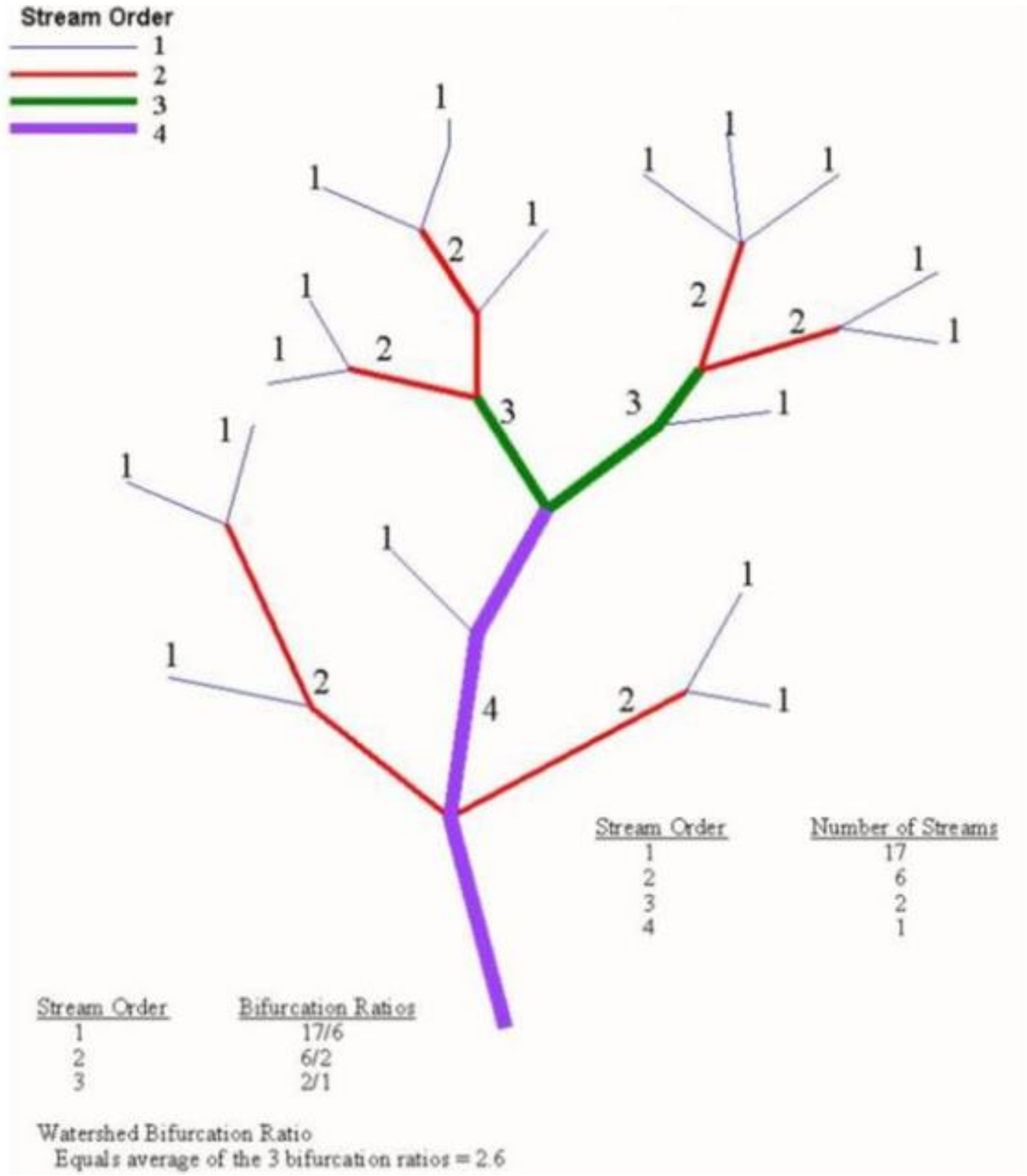
- Bifurcation Ratio is a dimensionless number denoting the ratio between the number of streams of one order and those of the next-higher order in a drainage network. The Bifurcation ratio looks at the relationship between streams of different orders.

Order	Number	$R_B(\omega)$
1.00	10.00	2.50
2.00	4.00	2.00
3.00	2.00	2.00
4.00	1.00	
Overall R_B		2.17



- Bifurcation ratio may be a useful measure of flood proneness – the higher the bifurcation ratio, the shorter will be the time taken for discharge to reach the outlet, and higher will be the peak discharge – leading to a greater probability of flooding. Bifurcation ratio correlates positively with drainage density i.e., a high bifurcation ratio indicates a high drainage density. Higher Bifurcation ratios also suggest that the area is tectonically active.

Bifurcation Example



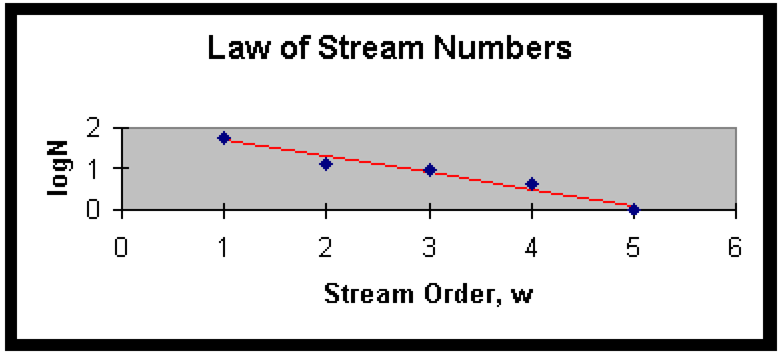
Hortons Law- Example

Obtain estimates of the Bifurcation Ratio, R_B, the Length Ratio, R_L, and the Area Ratio, R_A, using the data tabulated below.

Order, ω	Number of Streams	Average Length (km)	Average Area (km^2)
1	60	2	5
2	13	5	12
3	9	13	40
4	4	20	110
5	1	55	330

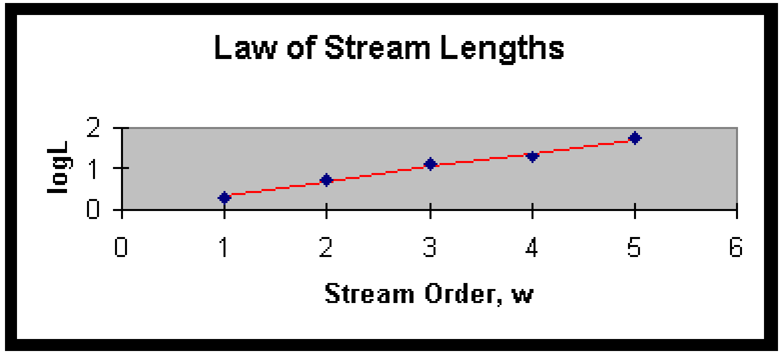
Order	Number of Streams	Average Length	Average Area	log(N)	log(L)	log(A)
1	60	2	5	1.778151	0.30103	0.69897
2	13	5	12	1.113943	0.69897	1.079181
3	9	13	40	0.954243	1.113943	1.60206
4	4	20	110	0.60206	1.30103	2.041393
5	1	55	330	0	1.740363	2.518514

A) Law of Stream Numbers and Bifurcation Ratio:



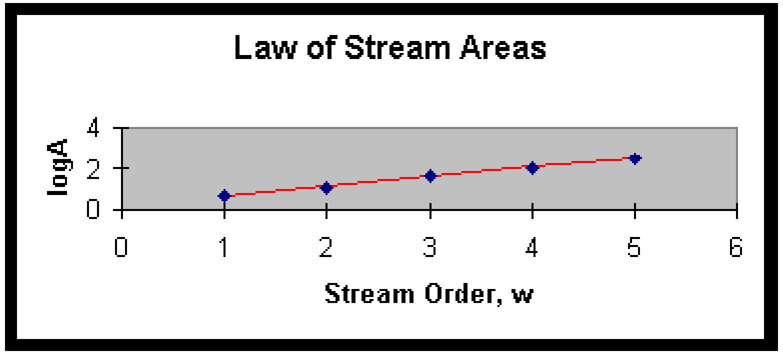
The linear regression analysis returns a slope *m* = -0.40682. Thus, R_B = 2.551635.

B) Law of Stream Lengths and Length Ratio:



The linear regression analysis returns a slope *m* = 0.348073. Thus, R_L = 2.228807.

C) Law of Stream Areas and Area Ratio:



The linear regression analysis returns a slope m = 0.46013. Thus, R_A = 2.884894.

D) The total length of streams can be calculated as:

$$L_T = \sum_{\omega=1}^{\Omega} N_\omega \bar{L}_\omega$$

Using the above equation leads to L_T = 437 km.

E) Drainage density:

$$D_d = \frac{L_T}{A_{\text{basin}}}$$

Thus, D_d = (437 km)/(330 km^2) = 1.3242 km^{-1}

F) Average length of overland flow:

$$L_o = \frac{1}{2D_d}$$

Thus, L_o = 0.377574 km = 377.74 m