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

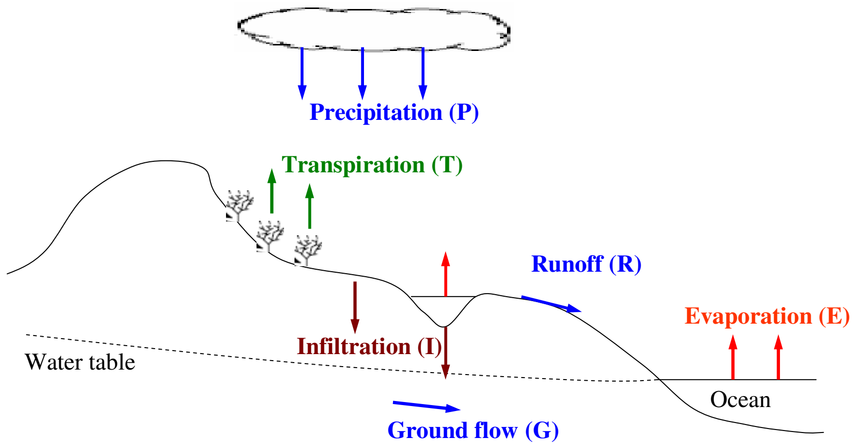
Jawa Dam

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.

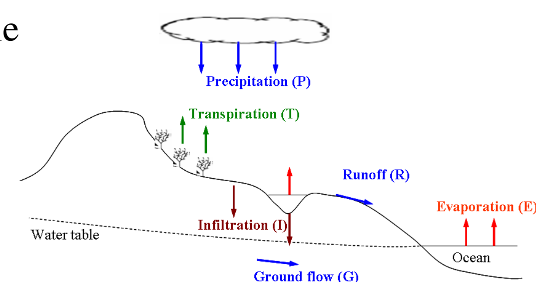


Hydrologic cycle

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

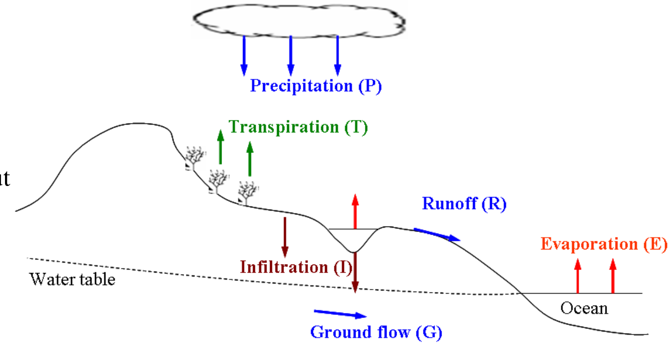
- Precipitation (P),
- Evaporation (E),
- Transpiration (T),
- Infiltration (I),
- Surface runoff (R), and
- Groundwater flow (G)



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

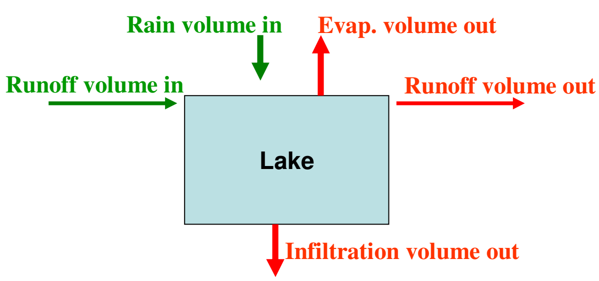
V_{out}: total water volume leaves the system

Hydrologic cycle

Ex: water balance application

A dam of 40km² lake receives average water flow of 0.56m³/s for January while delivers 0.48m³/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:

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

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

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

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

$= (1,499,904+1,800,000) - (1,285,632+5,000,000+1,000,000)$

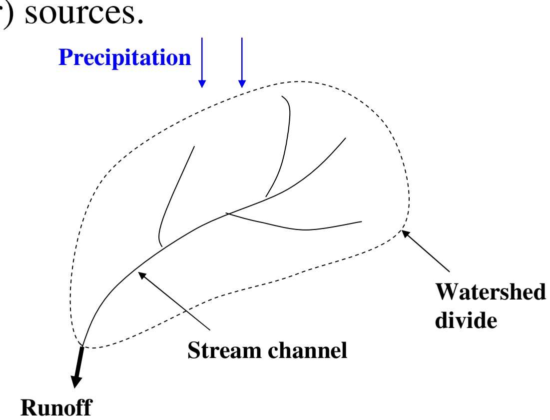
$= - 3,985,728 m^3$

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

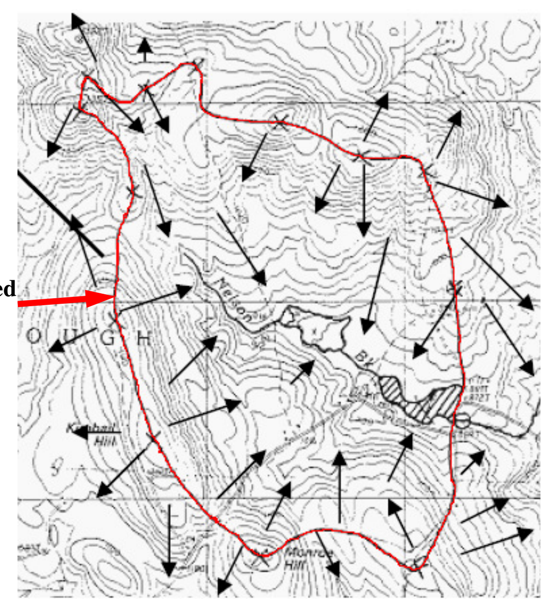
3- Mark flow directions from peaks of hilltops to cross contour lines at right angle.

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

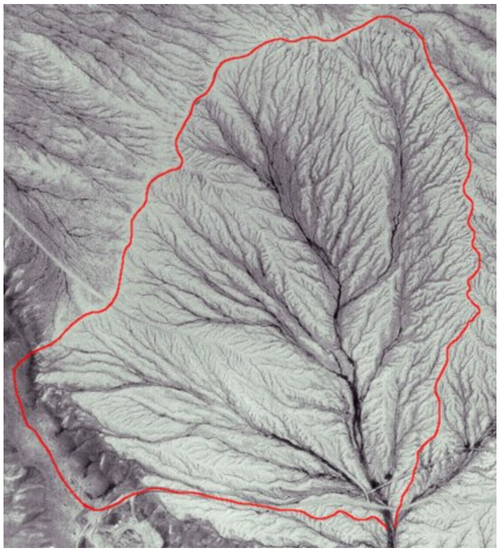
Watershed delineation

Example:

The resulted watershed



Watershed delineation using GIS



Watershed characteristics

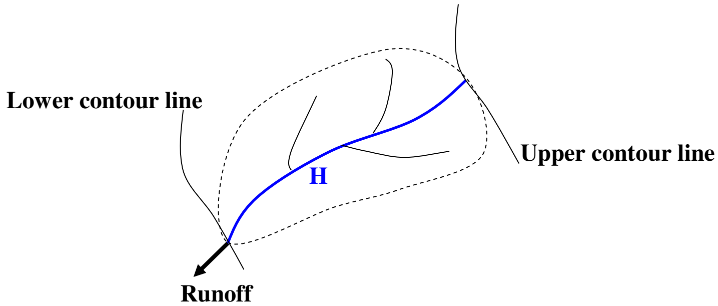
Watershed slope:

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.



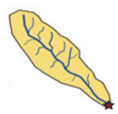
Watershed characteristics

Watershed shape:

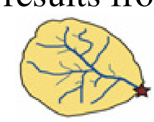
The watershed shape highly affects the flow amount (m^3/s) and the time needed to reach the peak flow. The watershed shape is a result of the watershed slope.

In general, two types of watershed shapes are recognized:

1- Elongated watersheds: results from steep slopes.

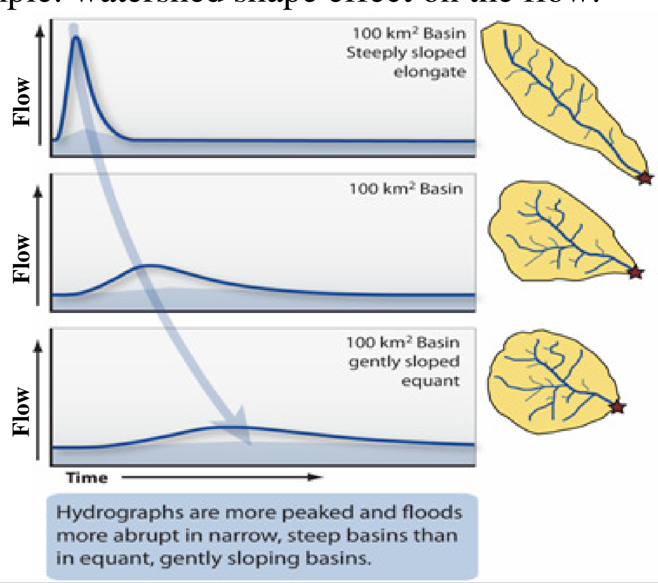


2- Equant watersheds: results from gentle slopes.



Watershed characteristics

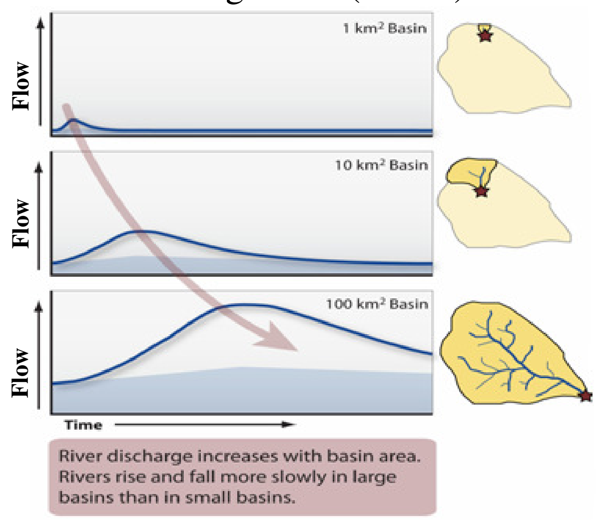
Example: watershed shape effect on the flow.



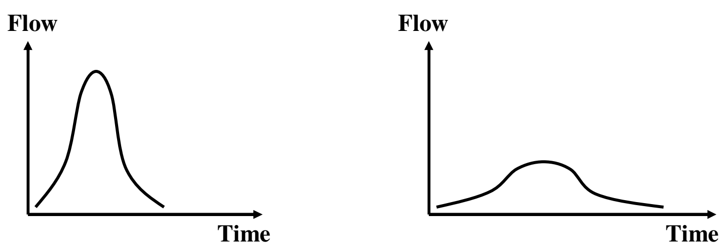
Watershed characteristics

Watershed contributing area:

Large areas contribute large flow (runoff).



Watershed characteristics



Case A

Case B

Steep watershed discharges flow like case …..

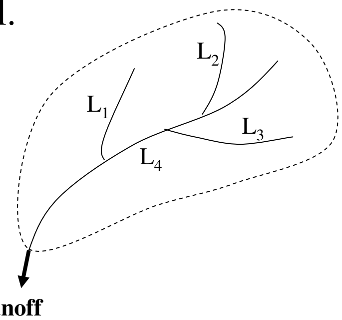
Watershed of rough surface discharges flow like case ….

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.

$k_A \approx k_B$

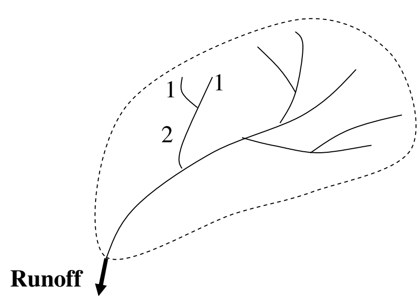
$$\frac{Q_A}{A_A} = \frac{Q_B}{A_B}$$

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

Watershed Bifurcation

Stream order and Horton laws:

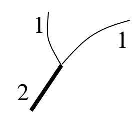
The stream order is used to classify watersheds. The order 1 is assigned to the smallest stream in the watershed, the order 2 is assigned to the next larger stream, and so on. The Horton laws can be used for computational purposes.



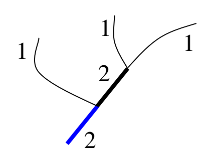
Watershed Bifurcation

Stream ordering rules:

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



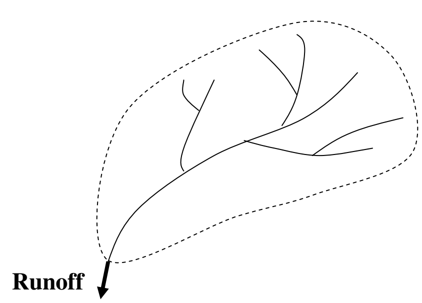
When a stream of order *i* meets a stream of order $i + 1$, then the stream formed has the order $i + 1$.



Watershed Bifurcation

Ex:

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

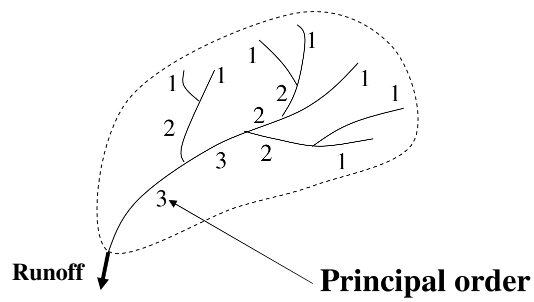


Watershed Bifurcation

Soln:

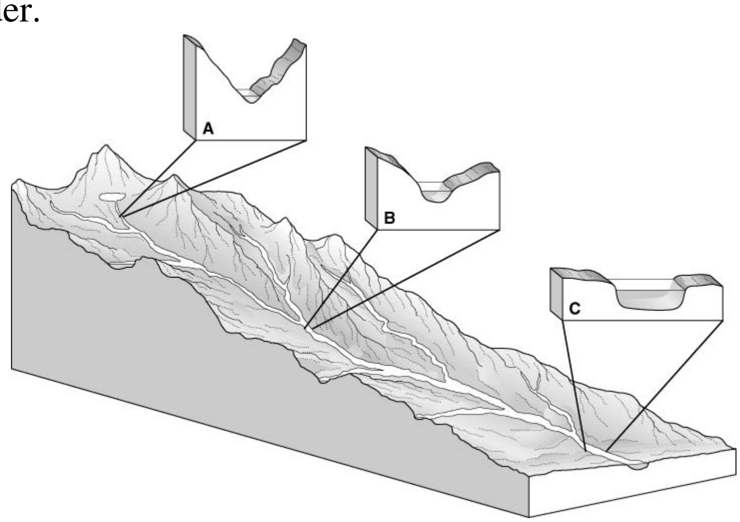
The first streams are labeled by the order 1, finish the solution using the rules mentioned previously. The principal order (k) = the largest order resulted.

$k = 3$



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.

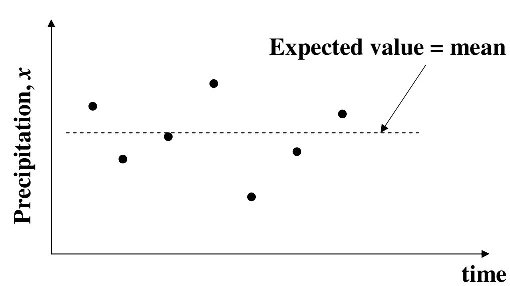
To deal with hydrologic random variables, statistical methods including the expectation, the variance, probability distribution functions, and frequency analysis are used. Such useful statistical methods will enable us to obtain the exceedance probabilities and return periods for design tasks, constructing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

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

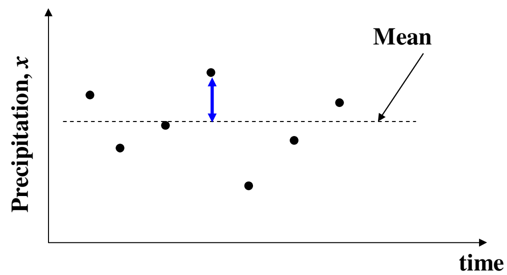


Statistical methods in hydrology

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.

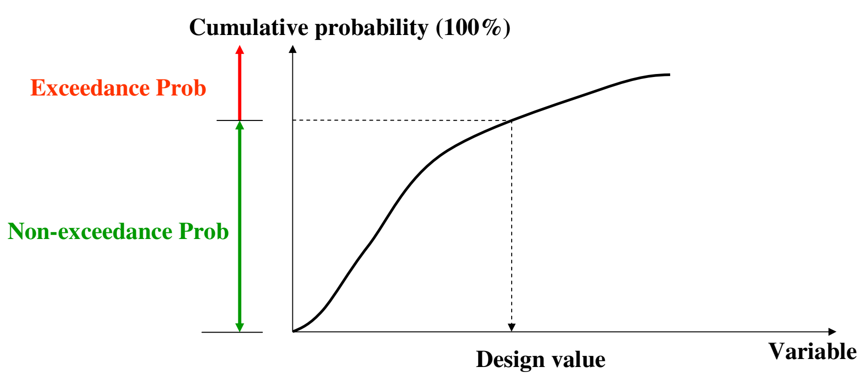
Examples from CE applications:

- 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 ≤ specified value x.
m: is data rank (lowest to highest).
n: record length.

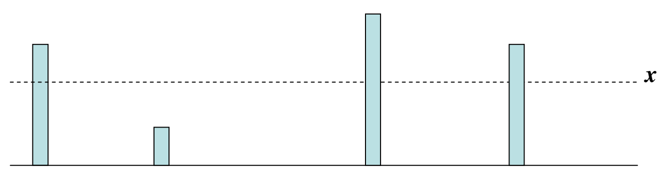
The probability $P(X > x) = 1 - P(X \leq x)$ is called the exceedance probability.

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

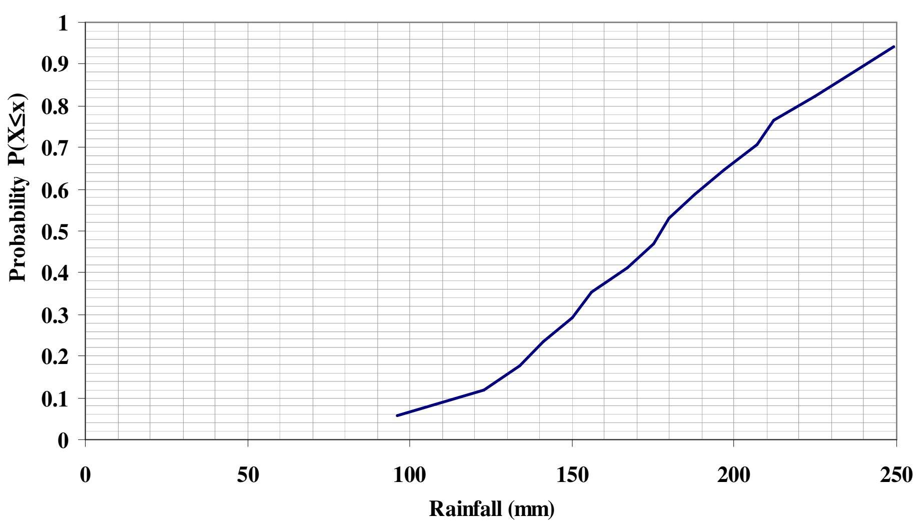
Soln: Arrange data from the lowest to highest. Rank the arranged data, and use the Weibull equation to calculate probability. n = 16.

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

Rank (m)	Rainfall (x)	$P(X \le x)$	Rank (m)	Rainfall (x)	$P(X \le x)$
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

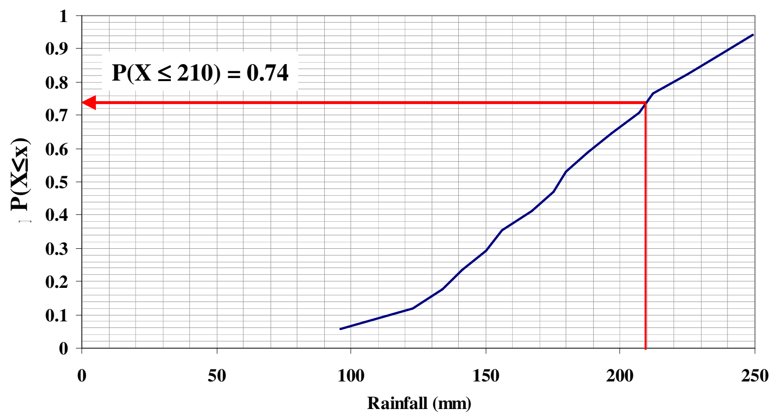
The probability distribution of the annual rainfall.



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),

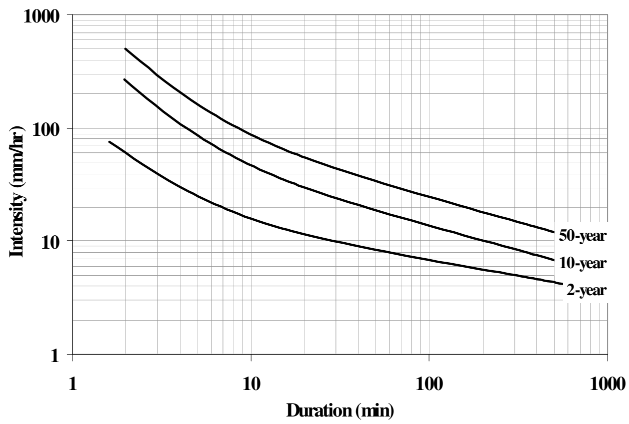
$$i(mm/hr) = \frac{x(mm)}{d(hr)}$$

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).

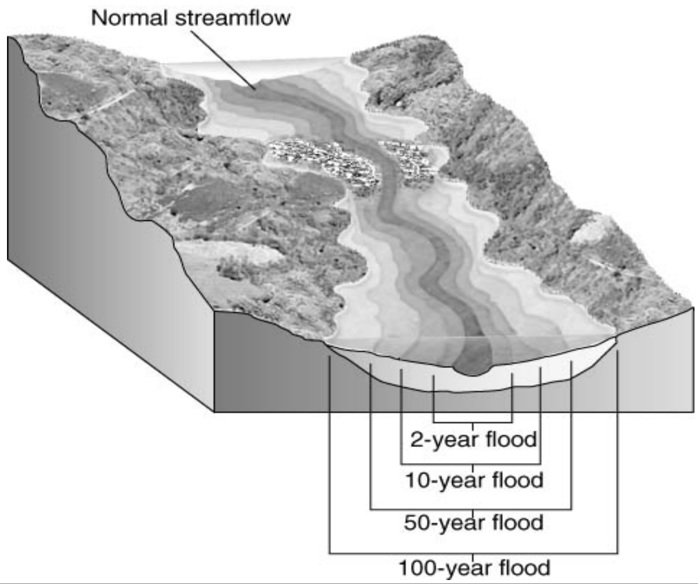
$$P(X \leq x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{x-u}{\alpha}\right]\right)\right]$$

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:

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

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

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

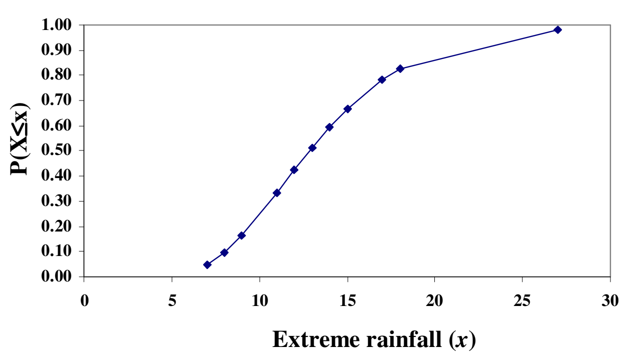
$$P(X \le x) = \mathbf{exp}\left[-\mathbf{exp}\left(-\left[\frac{x-u}{\alpha}\right]\right)\right]$$

Statistical methods in hydrology

Ex:

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

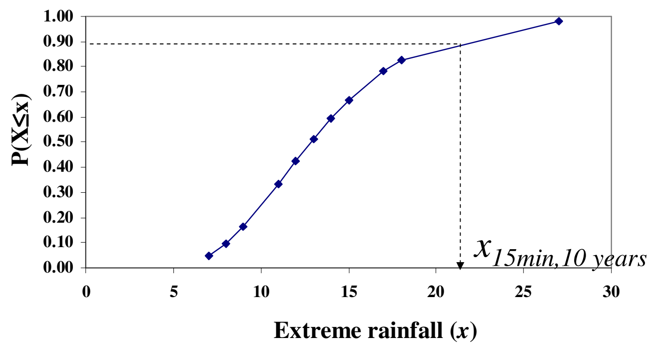
x	P(X ≤ x)
7	0.08
8	0.13
9	0.19
11	0.35
12	0.44
13	0.52
14	0.59
15	0.66
17	0.77
18	0.81
27	0.97



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.

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

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,

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

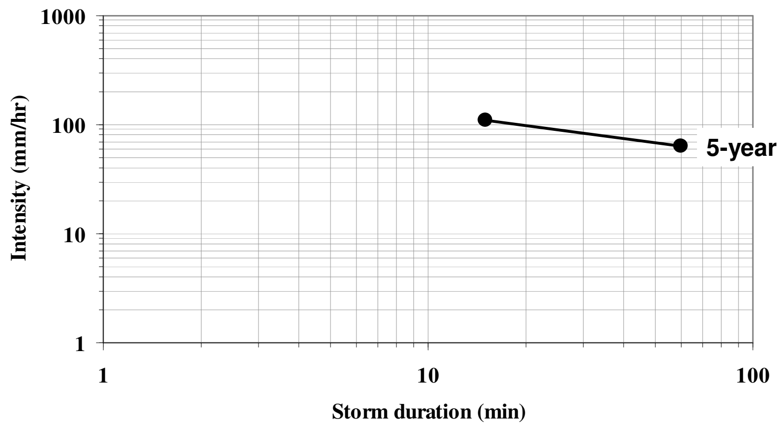
For 60-min, $x_{60,5}$ = 51.3 + 0.72×21.2 = 66.6mm

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: 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.

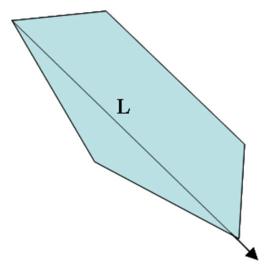
If the conditions mentioned above are not applicable, then the accuracy of the rational method is questionable. In that case the unit hydrograph, synthetic hydrographs and SCS method are used to estimate the peak runoff (will be discussed later).

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**:

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

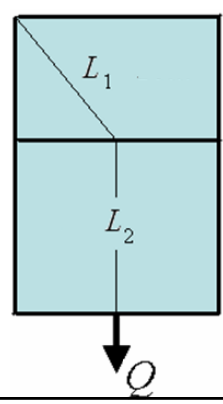


n: Roughness of surface
L: flow path distance (m)
S: surface slope

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).



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

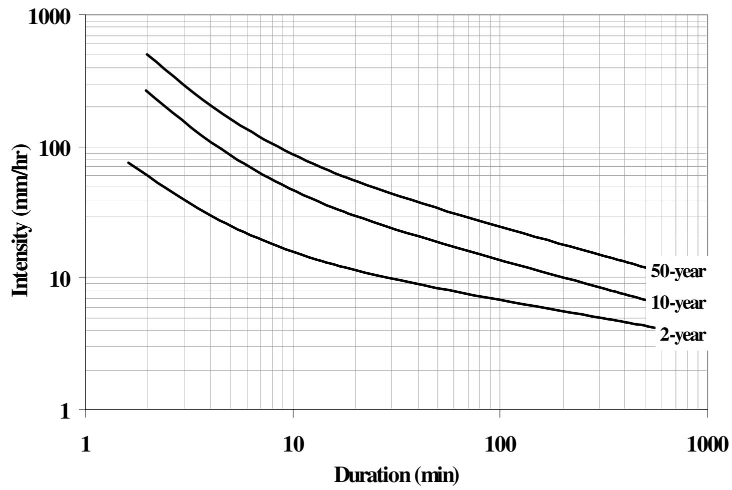
$S_1 = 1\%, n_1 = 0.025, L_1 = 220m$

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

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

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=

$= 0.828 \times (220 \times 0.025)^{0.467}/0.01^{0.235} = 5.4$ mins.

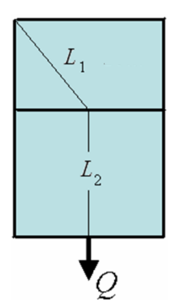
The time of concentration t_{c2} from sub-watershed 2=

$= 0.828 \times (250 \times 0.03)^{0.467}/0.015^{0.235} = 5.7$ 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 =

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

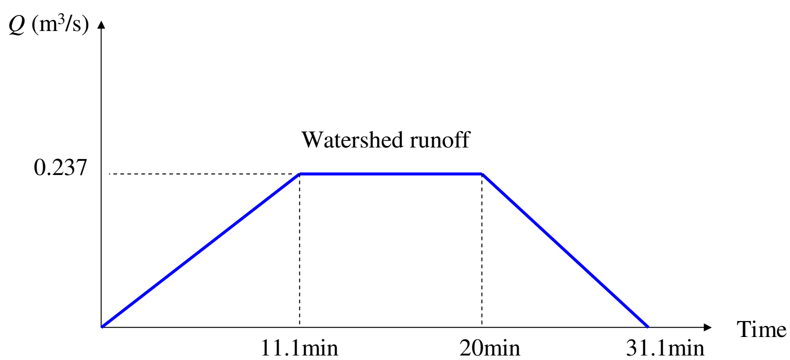
For t_c = 11.1mins < storm duration (20mins), and for T = 2 years then from the IDF-curves the storm intensity i = 11mm/h.

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

Micro-scale basin: measuring the runoff

Soln:

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



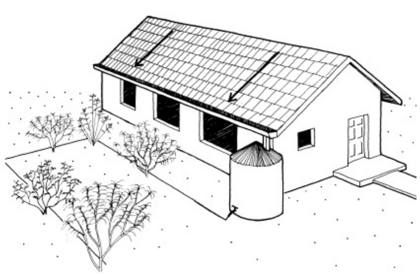
Micro-scale rainwater harvesting

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.

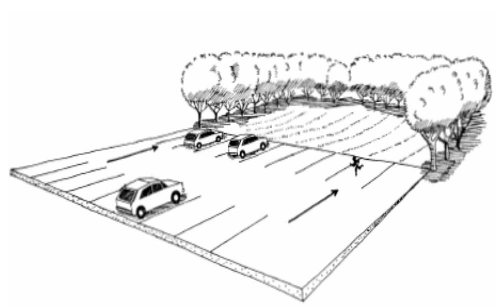
At an average rainy season, each single house rooftop in Jordan is able to collect about $10m^3$ of clean water. Just imagine that: if 50% of Jordanian house conduct such technique, what would be the amount of water collected? Do the simple math?

Micro-scale rainwater harvesting

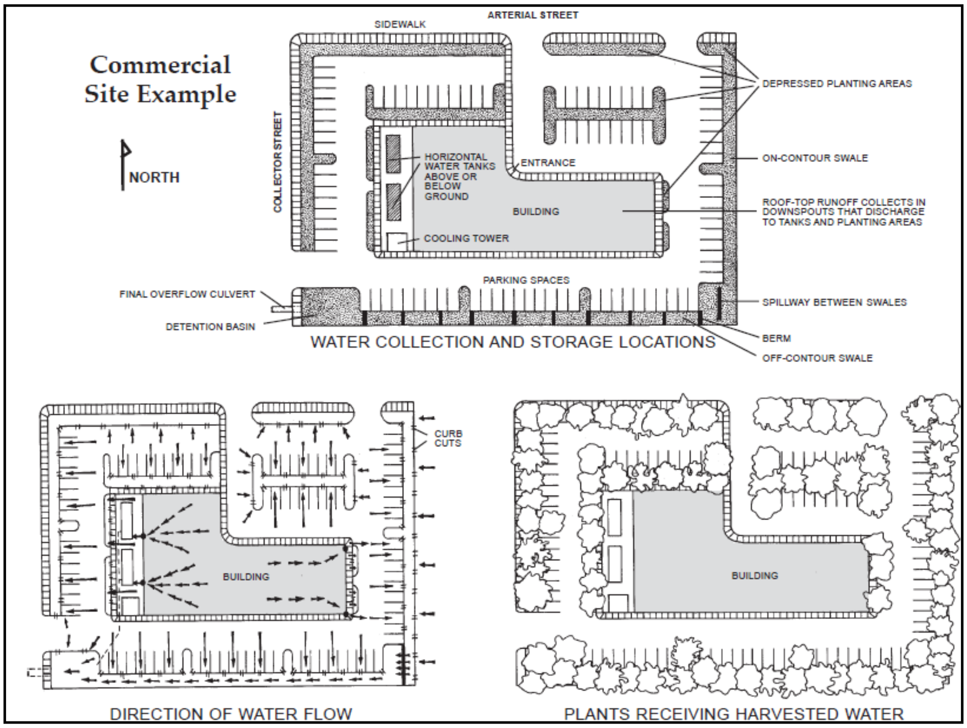
Example: micro-scale rainwater harvesting projects.



House rooftop

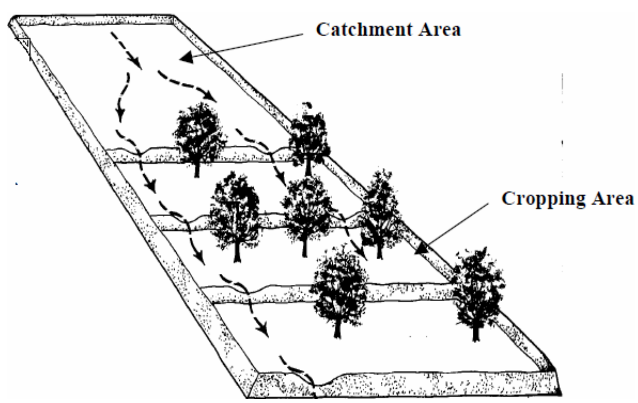


Parking lot



Micro-scale rainwater harvesting

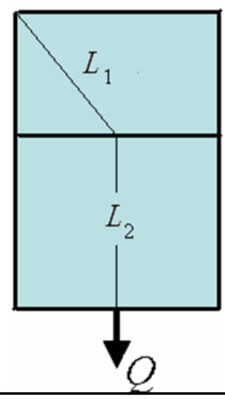
Example: micro-scale rainwater harvesting project (Cascade cropping area).



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.



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

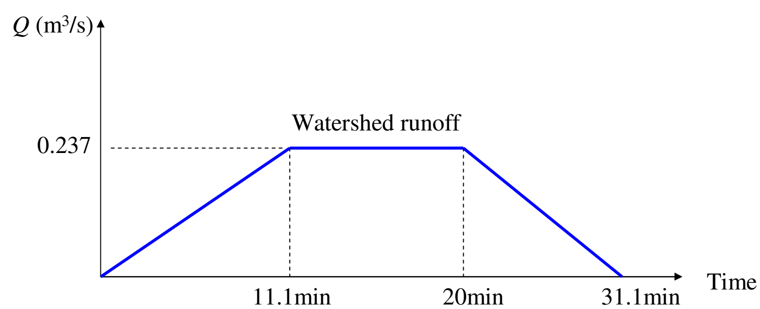
$S_1 = 1\%$, $n_1 = 0.025$, L_1=220m

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

$S_2 = 1.5\%$, $n_2 = 0.03$, 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:

$V = Q \times \text{time}$

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

$= 284\text{m}^3$

Engineering Hydrology

110401454

Hydrologic parameters

Instructor: Dr. Zeyad Tarawneh

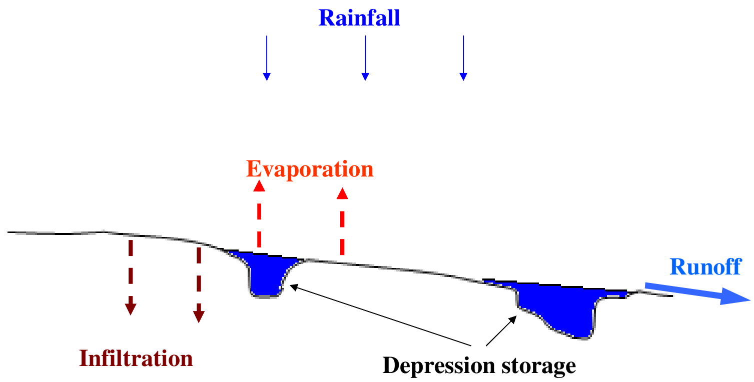
Macro-scale basin: measuring the runoff

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

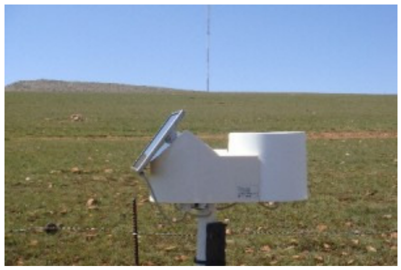
The first hydrologic parameter to be considered for the analysis is the precipitation. It is considered as the primary input variable in the hydrologic cycle and has the following forms: rain, snow or hail.

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, $W = 1/D^2$,

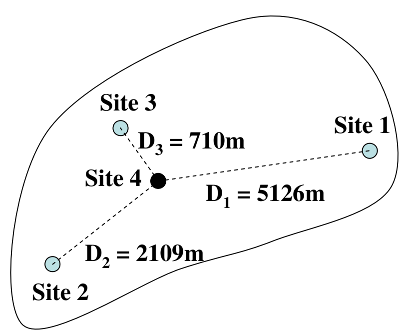
D: distance between the gauged and un-gauged site

Estimating the precipitation

Ex:

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

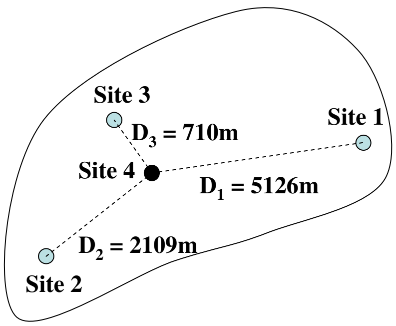
Site	rainfall (mm)
1	14
2	21
3	11



Estimating the precipitation

Soln:

Site	rainfall (mm)	D (km)	W	$P \times W$
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

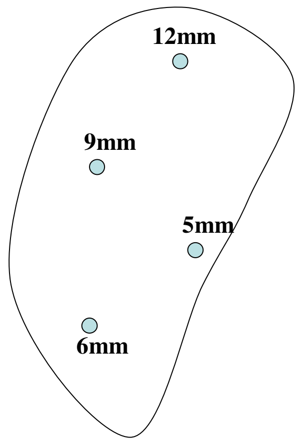
P: the precipitation in the thiessen polygon

A: area formed by thiessen polygons.

Estimating the precipitation

Ex:

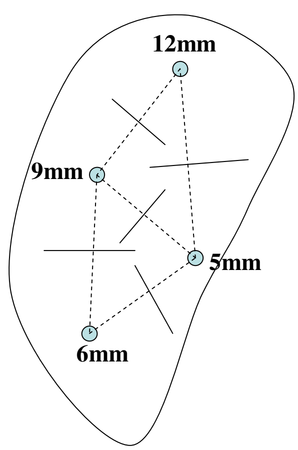
Estimate the areal rainfall for the following watershed.



Estimating the precipitation

Soln:

Connect the sites and bisect the distance between sites.



Estimating the precipitation

Soln:

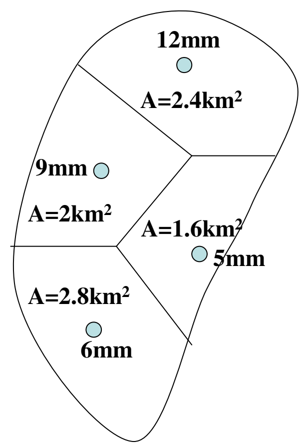
Calculate the area entrapped by each polygon.

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

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

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



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.

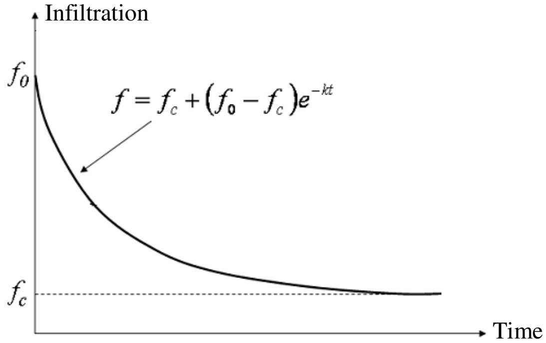
Hydrologic parameters: infiltration

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)

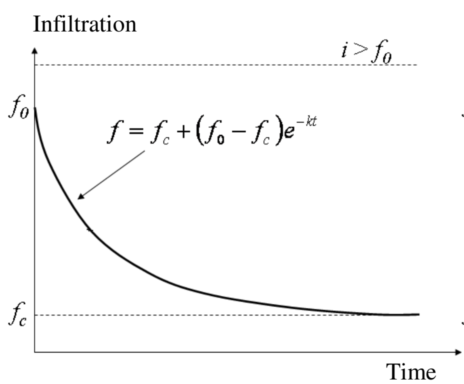
Hydrologic parameters



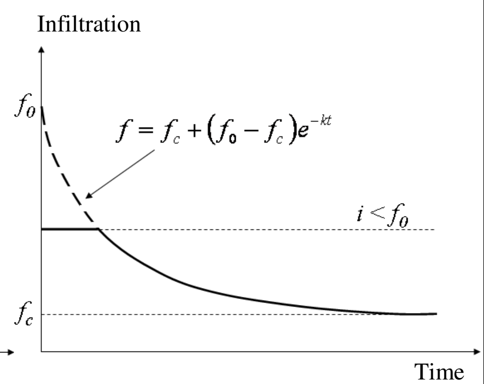
At time $t = 0$, the infiltration begins with its the initial infiltration rate f_0, however as time proceeds the infiltration rate decreases to reach its equilibrium infiltration f_c.

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:
$f = 0.75 + [5 - 0.75]e^{-0.29\times1} = 3.93$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:
$D_S = 2\,[1 - e^{(-6.15/2)}] = 1.9$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.

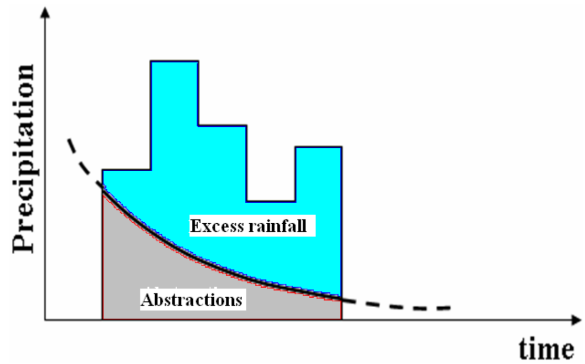
Hour	Gross rainfall intensity (mm/hr)	E_r (mm/hr)	f (mm/hr)	P_n (mm/hr)	D_S (mm/hr)	Net rain (mm/hr)
1	10.3	0.22	3.93	6.15	1.92	4.25
2	12.5	0.22	3.13	9.15	0	9.15

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

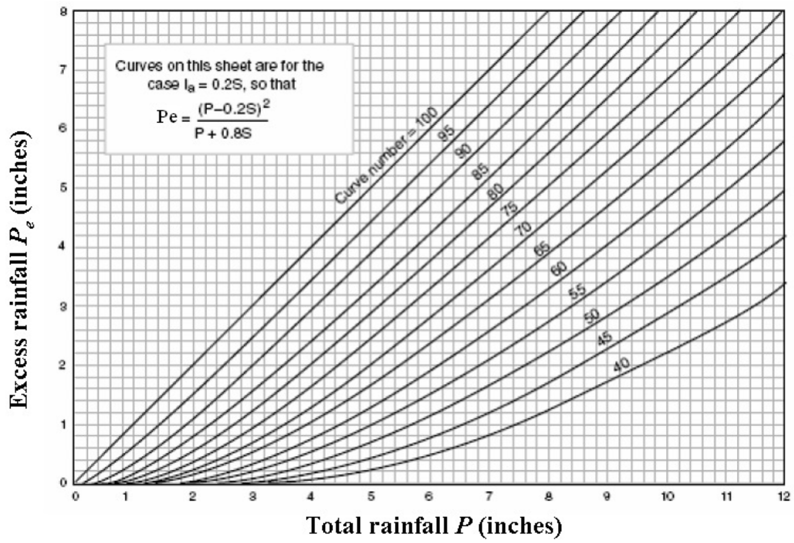
The SCS developed the method to calculate the excess rain for nearly flat watersheds (slope $\leq$ 5%). What will be the case for watersheds of slope > 5%? Think about it?.

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

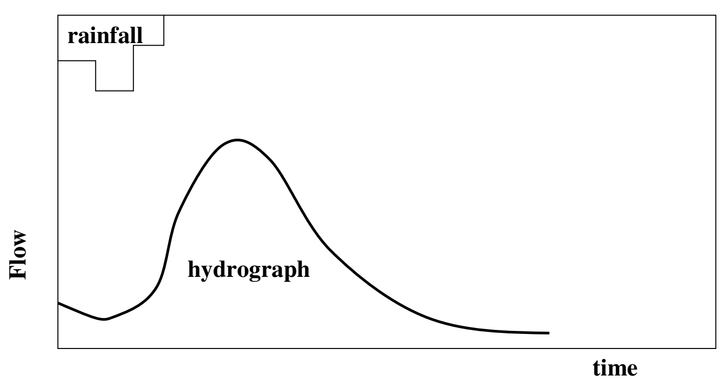
Macro-scale basin: measuring the runoff

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.



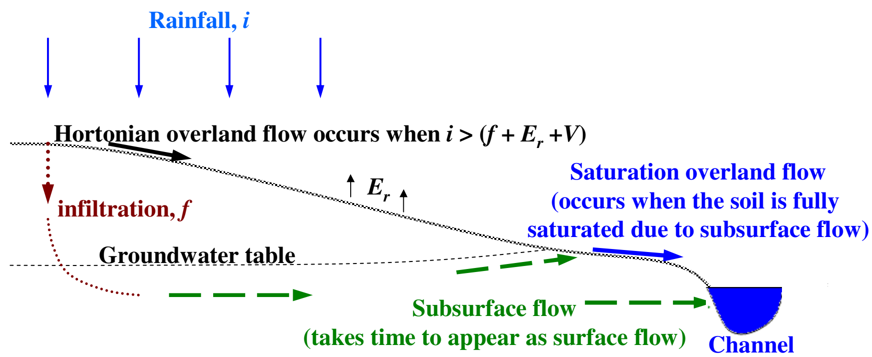
Hydrograph

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

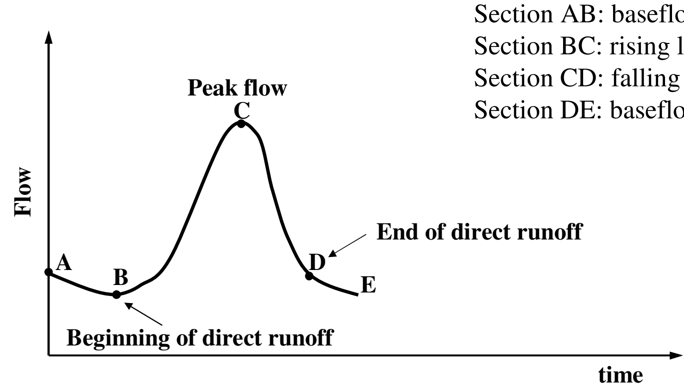
The following schematic plot defines the Hortonian overland flow, the subsurface flow, and the saturation overland flow.



Hydrograph

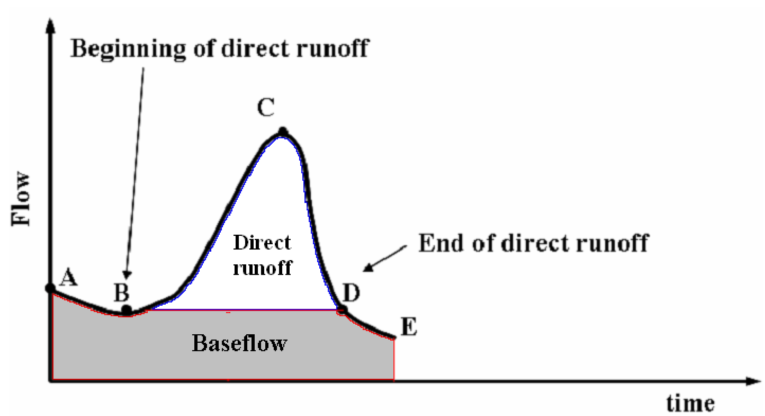
The following schematic plot defines a typical surface flow hydrograph from a watershed.

Hydrograph components
Section AB: baseflow recession
Section BC: rising limb
Section CD: falling limb
Section DE: baseflow recession



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

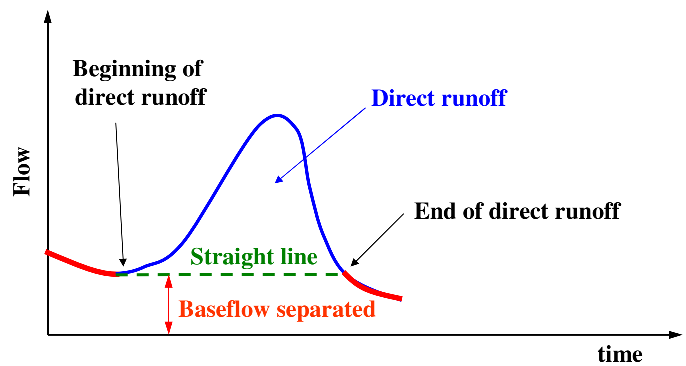
To study the watershed response (the direct runoff = surface runoff = overland flow) due to the cause (rainfall), then given the total runoff from the watershed, the base flow must be separated (extracted).

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:

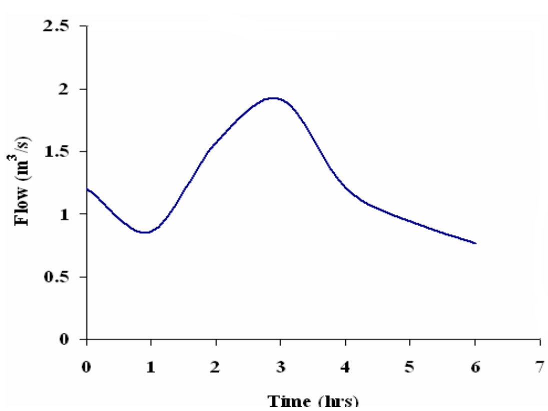
A large watershed discharges runoff to its outlet. The measured total runoff is shown in the table below. Estimate the direct runoff (surface runoff)?

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:

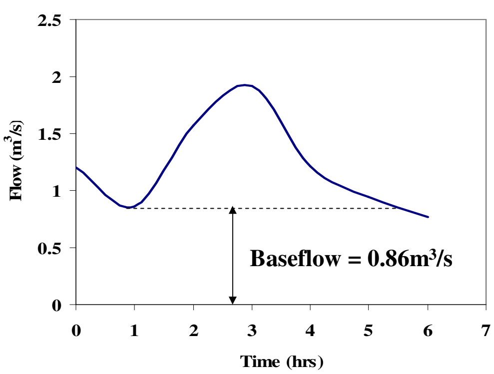
The following plot shows the hydrograph of the watershed total runoff. Observe the base flow recession portion and the rising limb. The baseflow will be at first separated using the straight line method.



Hydrograph

Soln:

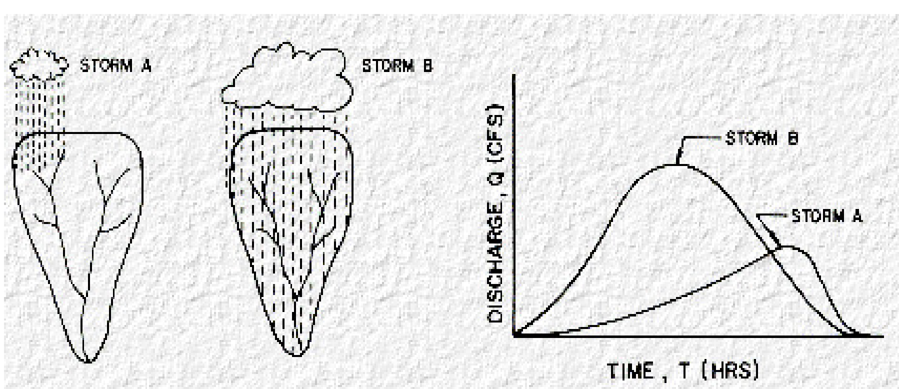
The direct runoff can be obtained after separating (subtracting) the baseflow from the total runoff. The direct runoff is the watershed response that will be used to derive the Unit Hydrograph.



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

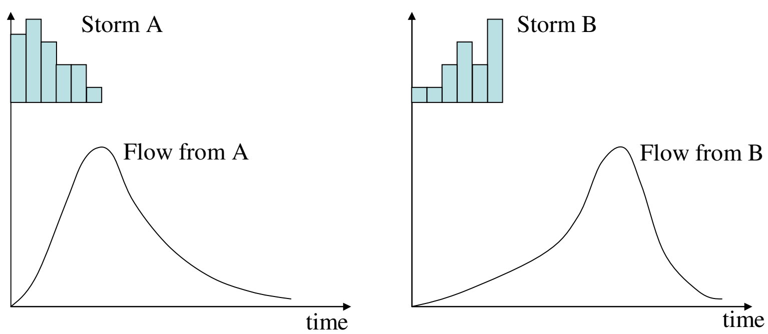
Hydrograph

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



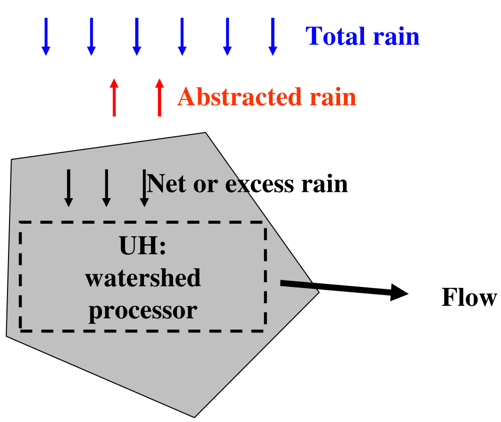
Hydrograph

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)

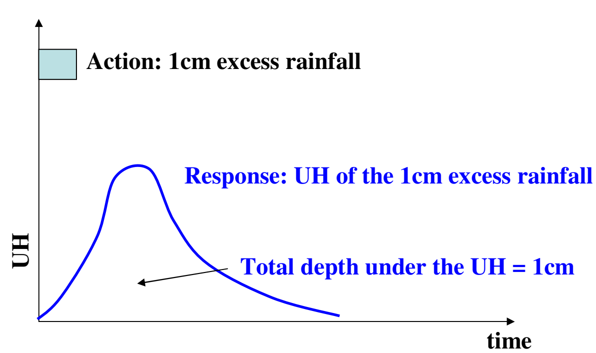
Therefore, the UH is defined as the watershed response through its direct runoff to an excess (net) rainfall of 1cm depth (unit depth). If the duration of the 1cm excess rainfall is X hrs, then the produced UH is called the X-hr UH. For example: 1-hr UH, 2-hr UH, and so on.

Assumptions:

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

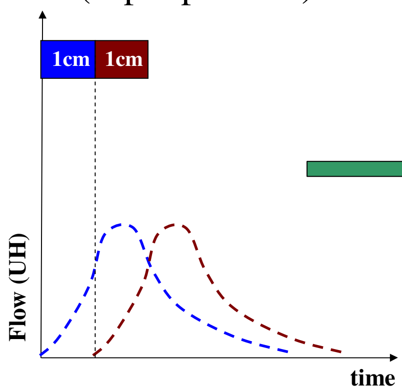
Unit Hydrograph

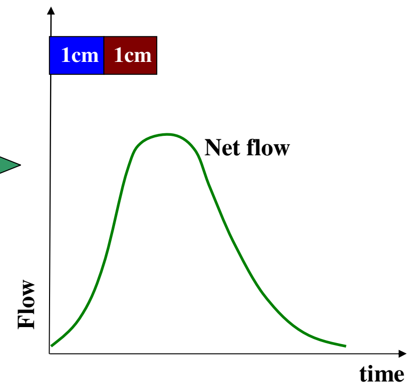
The plot below presents the idea of the UH. The action (pulse) is the 1cm excess rainfall. The response is the direct runoff that has total depth of 1cm, distributed over the time according to the water travel time to the watershed outlet.



Unit Hydrograph

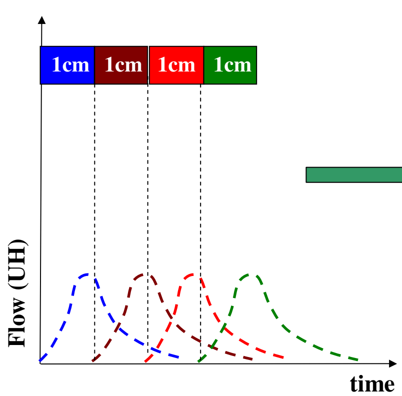
Assume a watershed of X-hr UH is subjected to a 1 cm net rain storm of 2X duration, then the storm has 2 pulses each of X duration and 1cm excess rain. Each will produce its own flow and the net flow will be the sum (super position) of the two flows.

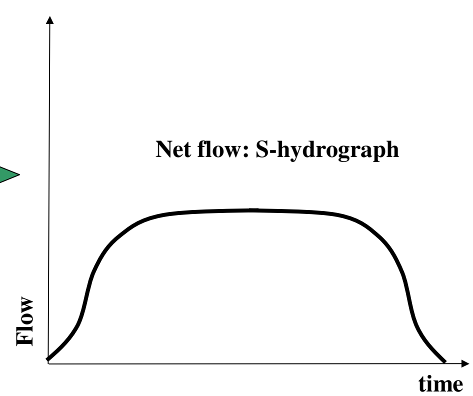




Unit Hydrograph

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:

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

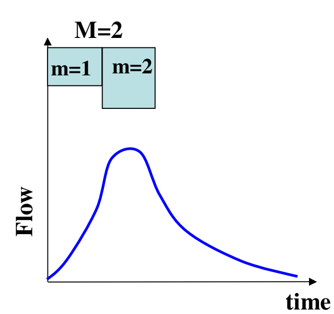
where

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:

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

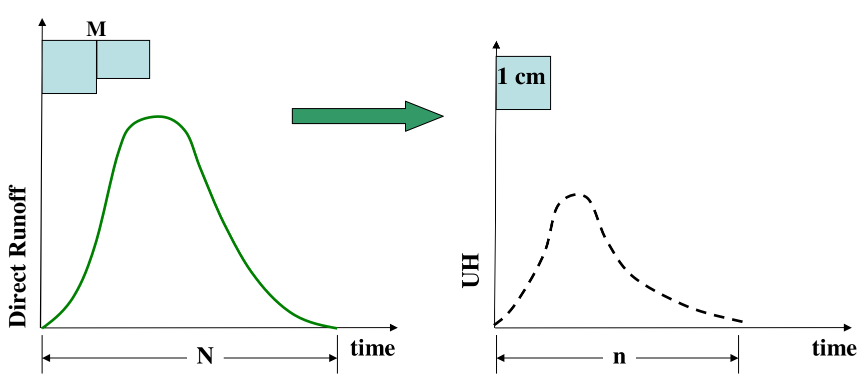
Question:

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, $Q_1 = P_1 U_1 \Longrightarrow U_1 = \frac{Q_1}{P_1}$

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 $n = 4$.

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

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

Deriving the UH

Soln:

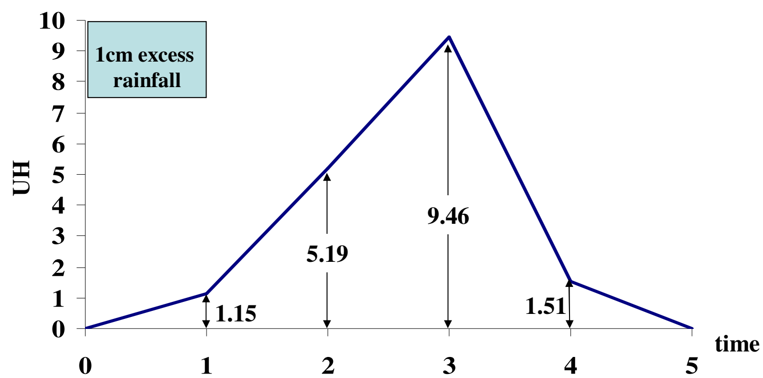
Results are shown below.

Time (hr)	Excess rainfall (cm)	Direct runoff (m³/s)	Equation	UH (m³/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:

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

at $n = 1$, $Q_1 = \sum_{m=1}^{1} P_m U_{1-m+1} = P_1 U_1$ = 0.8×1.15 = 0.92m³/s

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

= 0.8×5.19 + 1×1.15 = 5.3m³/s.

Measuring the surface runoff

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

= 0.8×9.46 + 1×5.19 + 0.5×1.15= 13.33m³/s

Why 3 ??

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

= 0.8×1.51 + 1×9.46 + 0.5×5.19 = 13.26m³/s.

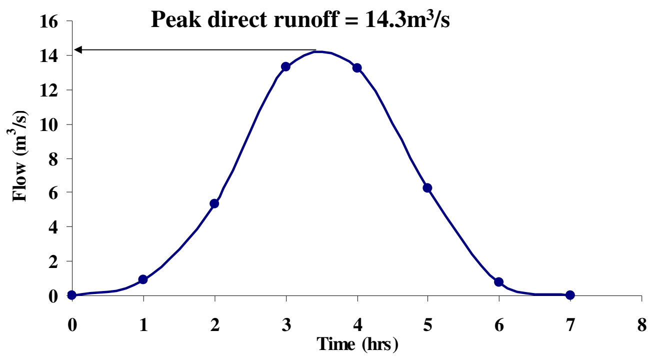
and so on……

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:

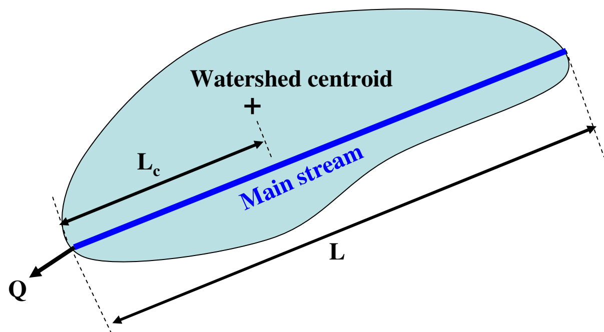
When the watershed has gauging stations to measure the actual *Q* resulted from given excess rainfall *P,* then the UH can be derived as shown previously. However, most of watersheds may not have gauging stations, therefore synthetic hydrographs is used to estimate the peak discharge.

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:

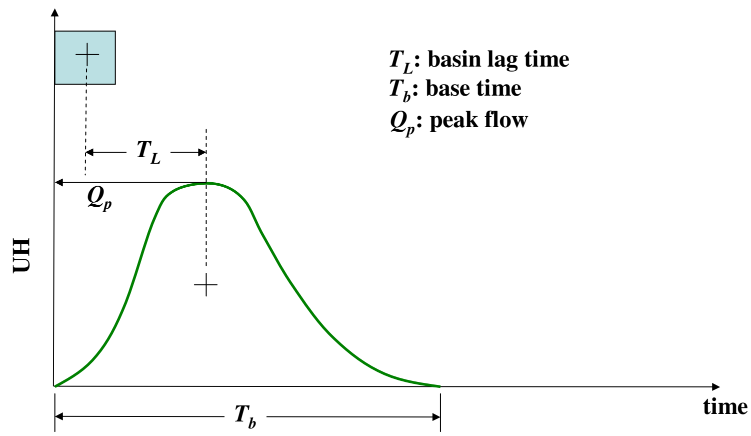
Snuder developed equations (models) to measure the time and peak flow based on ***observations*** and such models need corrections. The coefficients C_t and C_p are corrections for the time and the amount of peak flow.

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:

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

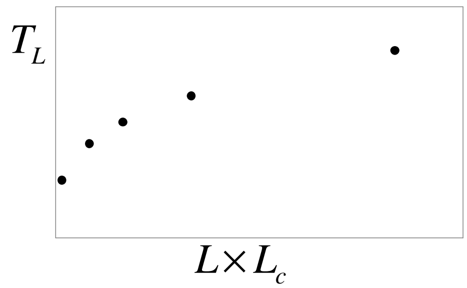
T_L (hr), L & L_c (km)

The duration of the excess rainfall is:

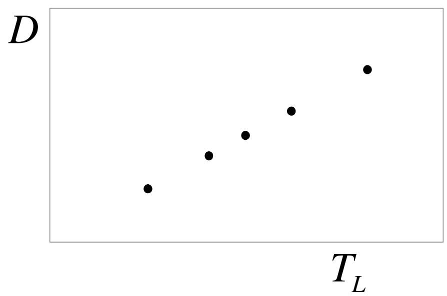
$$D = \frac{T_L}{5.5}$$

D (hr)

Measuring the surface runoff



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



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

Measuring the surface runoff

Procedure to derive the Snyder’s UH:

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

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

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:

$$Q_p = \frac{2.78 C_p A}{T_L'}$$

Q_p (m^3/s), T_L (hr)

The time to peak flow occurrence is:

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

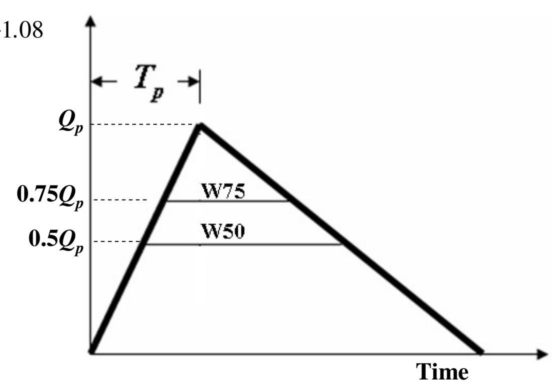
Measuring the surface runoff

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.

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

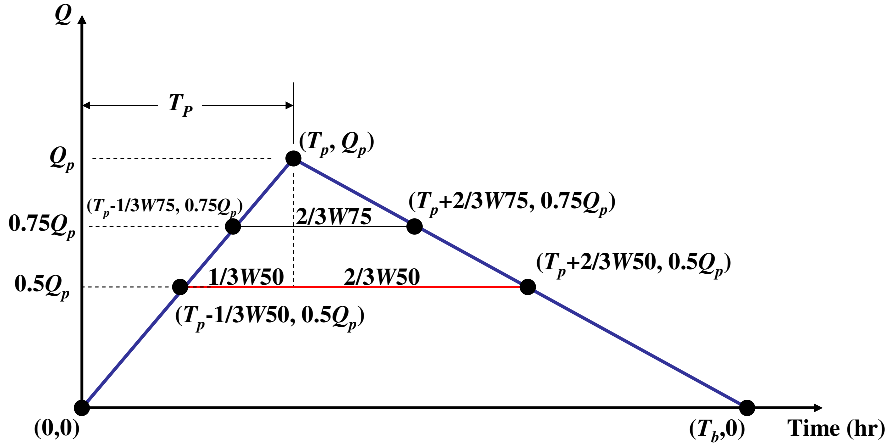
$$W75 = \frac{W50}{1.75}$$



Measuring the surface runoff

Procedure to derive the Snyder's UH:

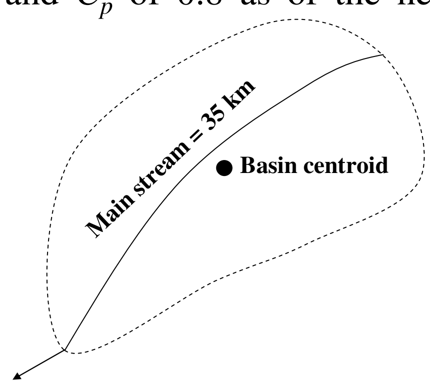
On the UH seven points will be available.



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.



Measuring the surface runoff

Soln:

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

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

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

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

Measuring the surface runoff

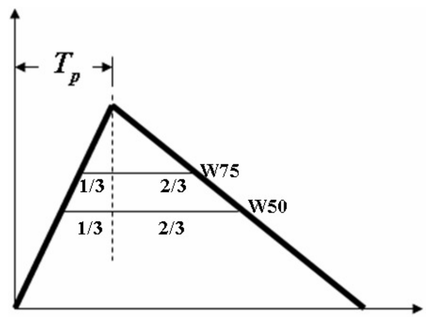
Soln:

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

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

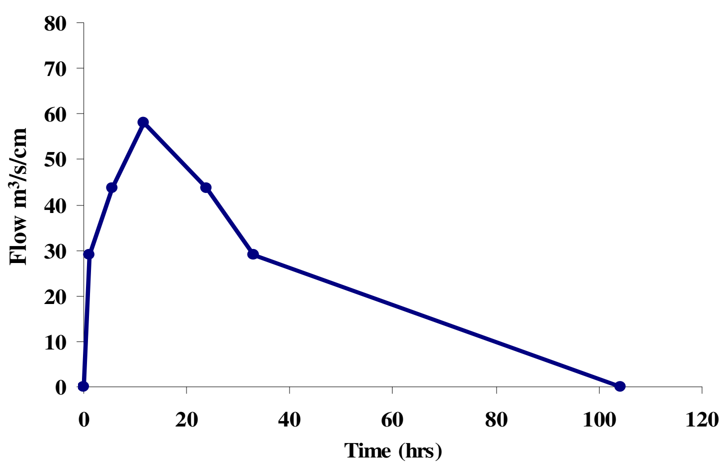
$T_p = 11.72$ *hrs*.

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).

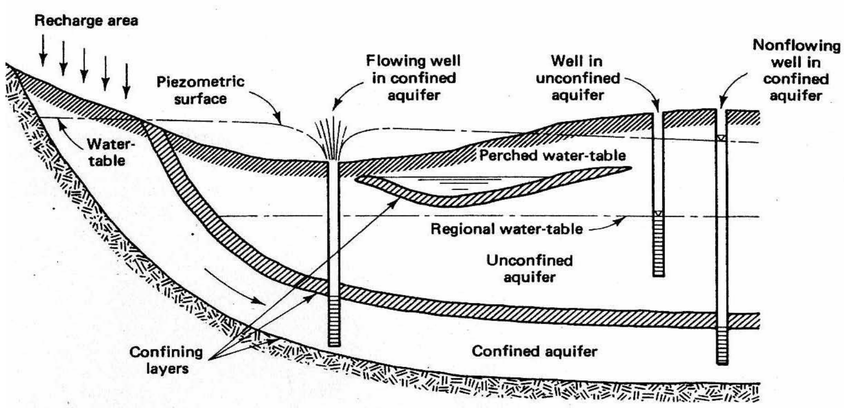
Groundwater hydrology

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:

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

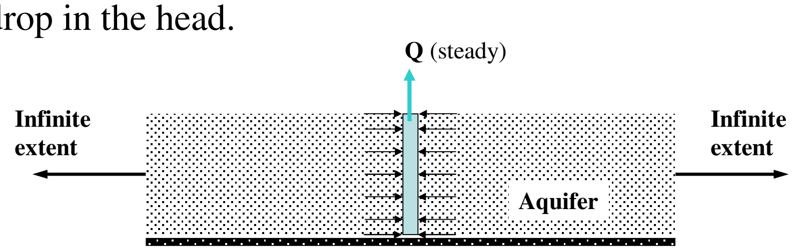
k: constant called the hydraulic conductivity,
∂h: drop in hydraulic grade line between 2 observation points,
∂r: horizontal distance between 2 observation points,
s: the hydraulic gradient.

Groundwater hydrology

Equilibrium analysis of the groundwater flow:

The equilibrium analysis to solve the Darcy equation assumes that:

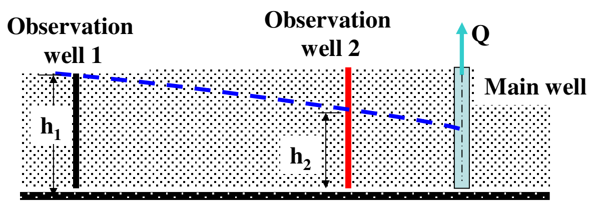
- the flow rate from the aquifer is constant (*steady*),
- the well is screened through the entire aquifer depth,
- the aquifer is uniform of infinite extent (Isotropic),
- the water is released immediately in response to a drop in the head.



Groundwater hydrology

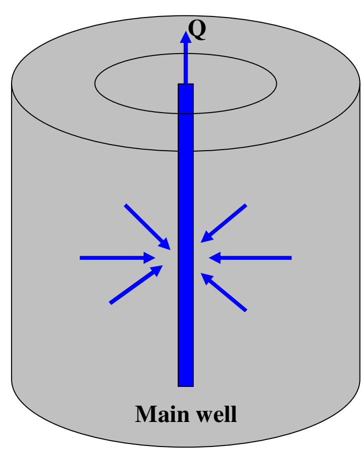
Observation wells:

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.



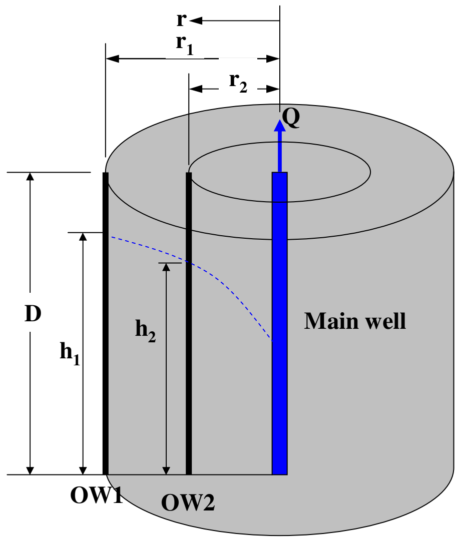
Groundwater hydrology

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



Groundwater hydrology

Steady radial flow:



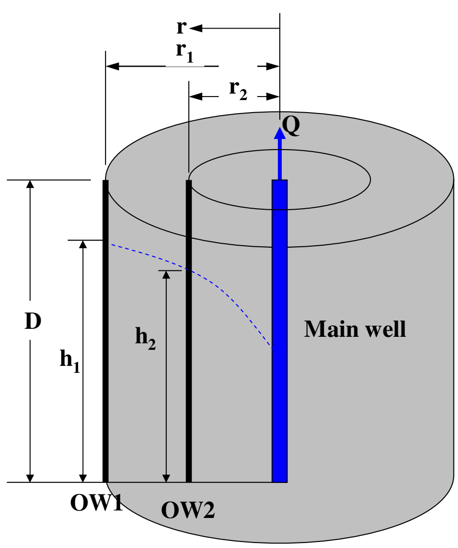
$$V = k\frac{dh}{dr}$$

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

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

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,

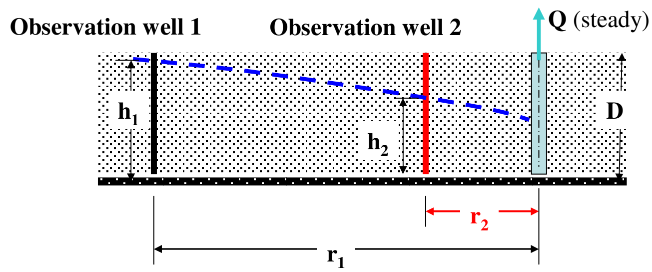
r_1 and r_2: the radial distances to observation wells 1 and 2.

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?

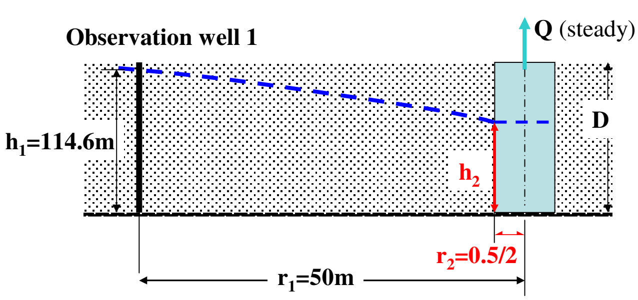
$$Q = \frac{2\pi k\, D(h_2 - h_1)}{\ln(r_2 / r_1)} = 0.025 = \frac{2\pi k(15)(112.5 - 114.6)}{\ln(20/50)}$$

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:

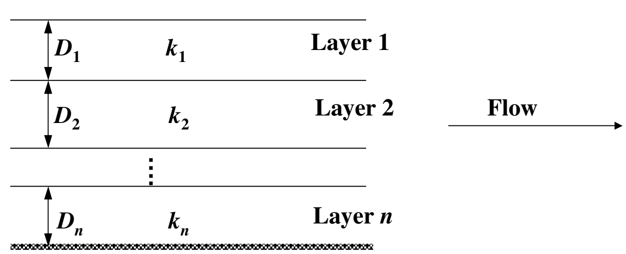
When the aquifer material varies either horizontally or vertically, then the aquifer is anisotropic and hence an average k should be used. This case is more realistic than assuming that the aquifer is totally isotropic (k is constant), however in reality, the aquifer contains materials that differ in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

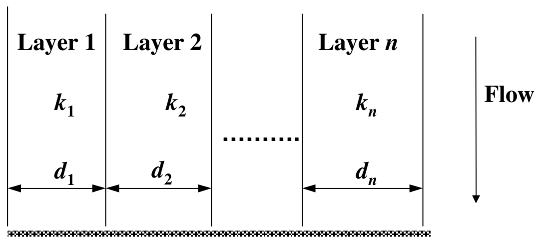


$$k_H = \frac{k_1 D_1 + k_2 D_2 + \dots\dots\dots + k_n D_n}{D_1 + D_2 + \dots\dots + D_n}$$

Groundwater hydrology

The equivalent vertical hydraulic conductivity:

Assume an aquifer of vertical layers 1, 2, ..,*n*.



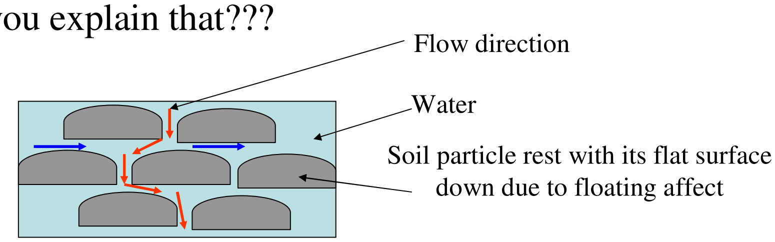
$$k_V = \frac{d_1 + d_2 + \dots\dots + d_n}{\frac{d_1}{k_1} + \frac{d_2}{k_2} + \dots\dots + \frac{d_n}{k_n}}$$

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

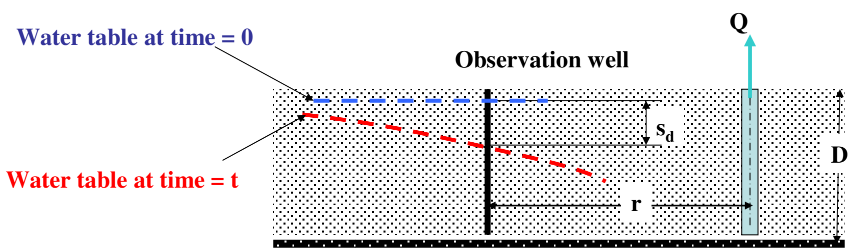
Nonequilibrium analysis:

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):

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

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



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

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. 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:

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

$$s_d = \frac{0.025}{4\pi\left(\frac{150}{86400}\right)}\ln\left(\frac{2.25(150)t}{(20)^2\times 10^{-4}}\right)$$

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:

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

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

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

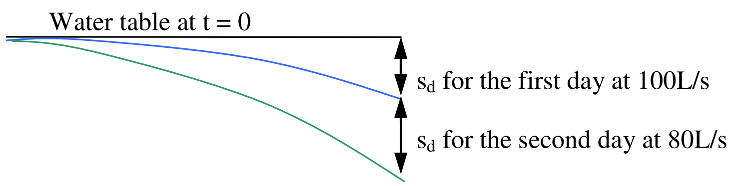
Drop in the groundwater table

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

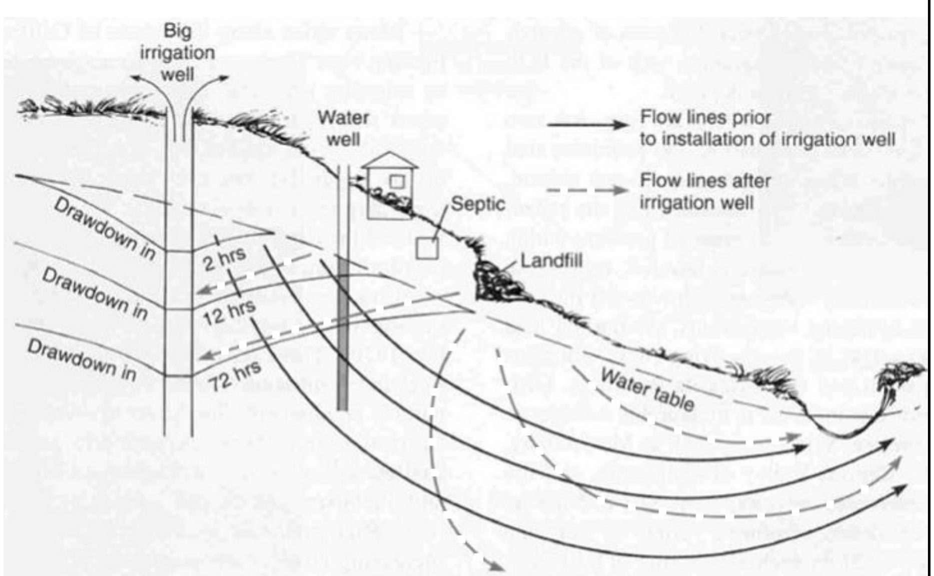
= s_d at 100L/s for the first day + s_d at 80L/s for the second day

= 12.238 + 1.906

= 14.144m



Drop in the groundwater table



Drop in the groundwater table

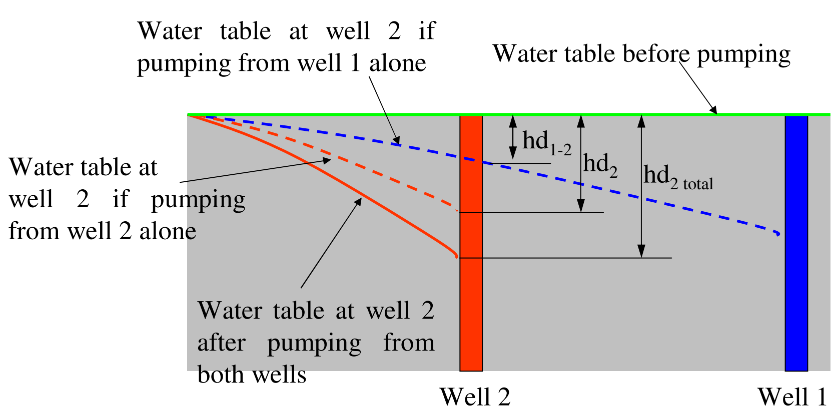
Multiple well system:

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

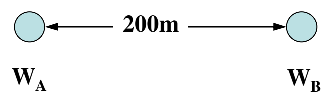
Observe the effect of well 1 on well 2 just.



Drop in groundwater level

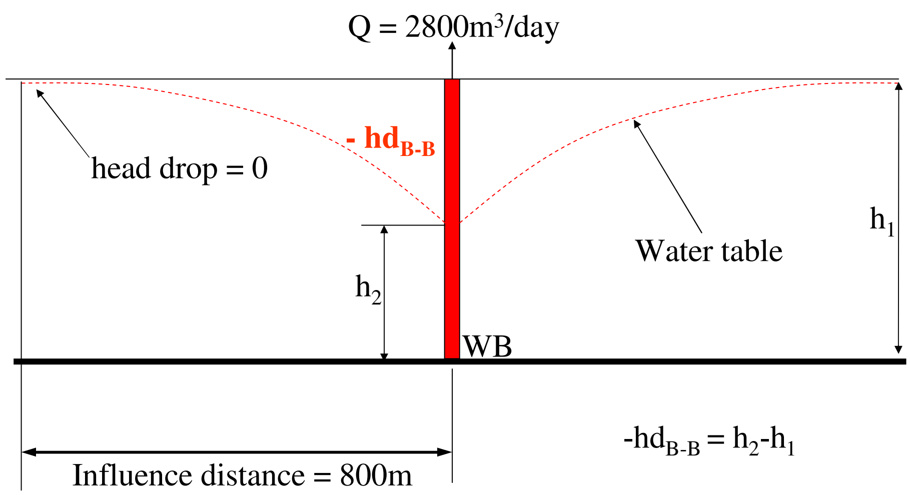
Ex:

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.



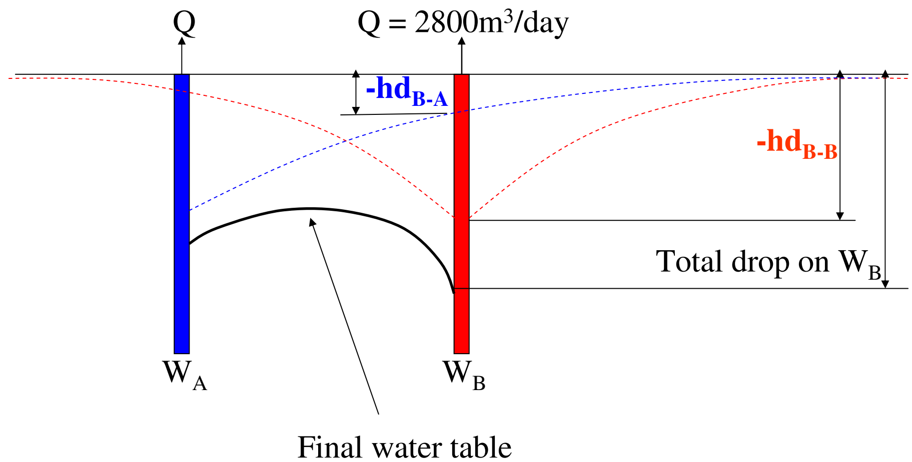
Drop in groundwater level

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:
$T = 2400/86400 = 0.0278\text{m}^2/\text{s}$. $Q_2 = 2800\text{m}^3/\text{d} = 0.032\text{m}^3/\text{s}$.

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}) ≤ - 2m.

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

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 $hd_{B\text{-}A} \leq 0.48m$.

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

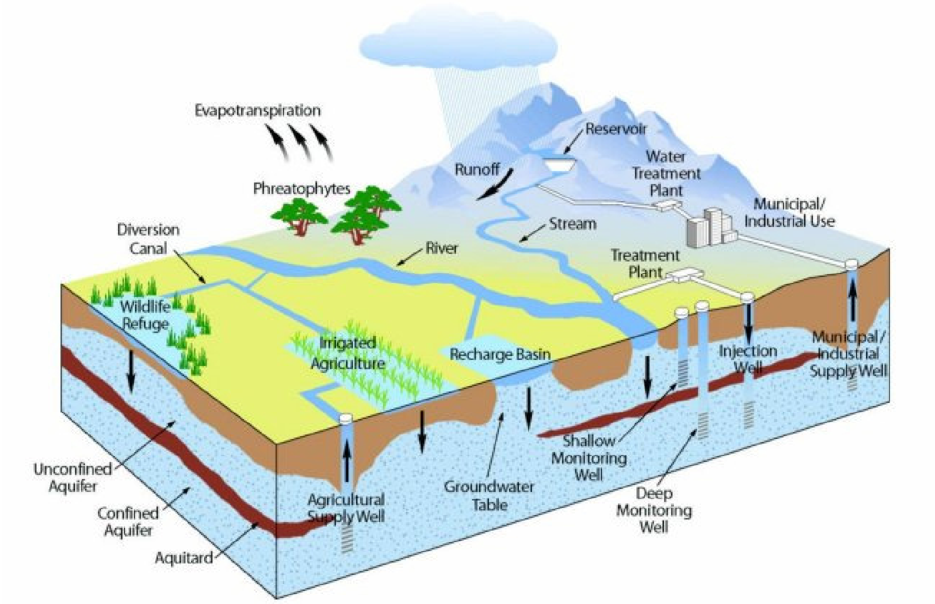
$$Q_A = \frac{2\pi \times 0.0278(-hd_{B-A})}{\ln(800/200)} =$$

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

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).

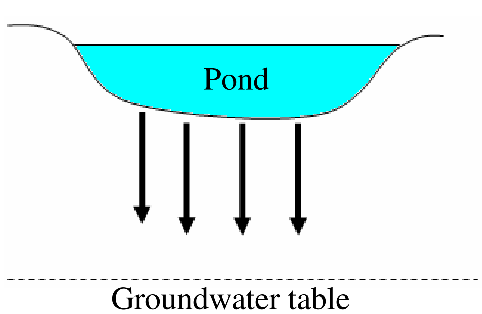
Groundwater artificial recharge



Groundwater artificial recharge

Techniques of artificial recharge:

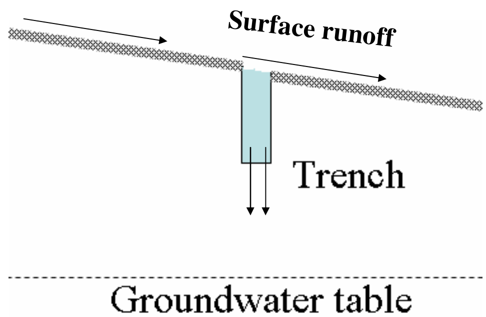
- Infiltration pond (recharge basin): are natural soil ponds placed next to major surface runoff streams to store surface water and allow the infiltration through soil to the underlying unconfined aquifer.



Groundwater artificial recharge

Techniques of artificial recharge:

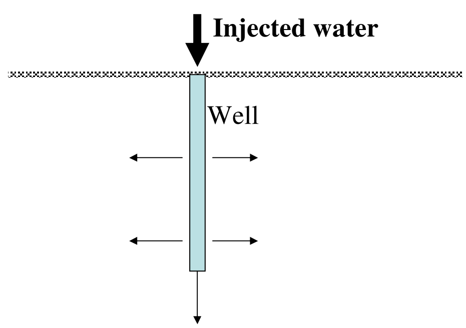
- Trenches: are structures in natural soil placed sloppy lands to intercept surface runoff and store water and allow the infiltration through soil to the underlying unconfined aquifer.



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:

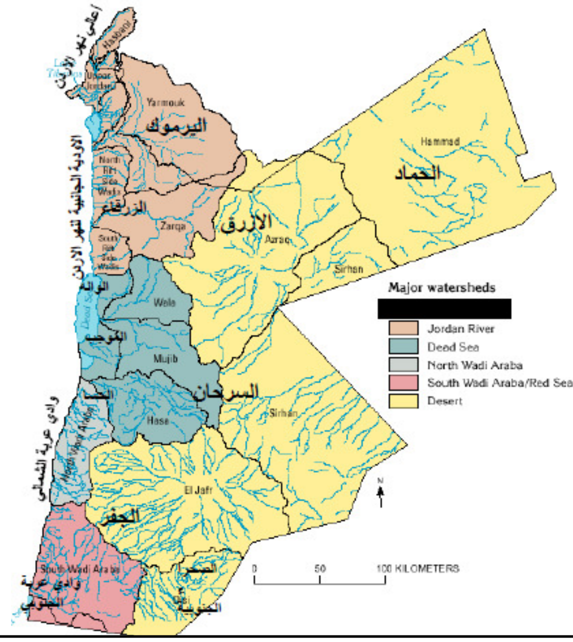
Source	amount (Mm^3)
Renewable groundwater	280
Non-renewable groundwater	140
Surface water	750
Treated wastewater	100
Brackish water (ready for desalting)	70

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

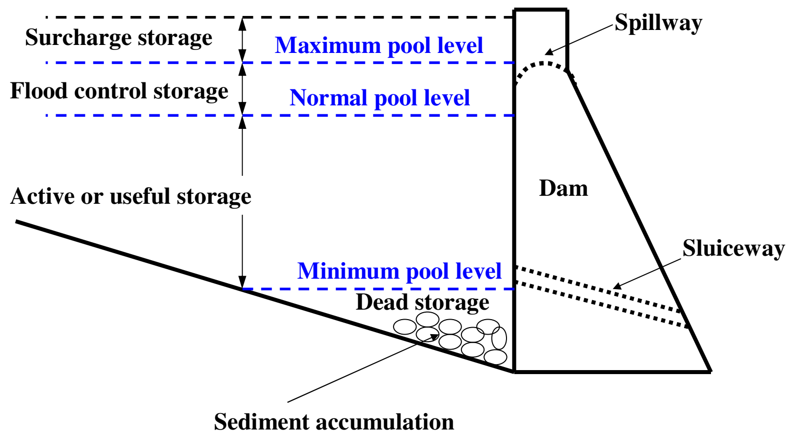
Reservoir storage components:

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:

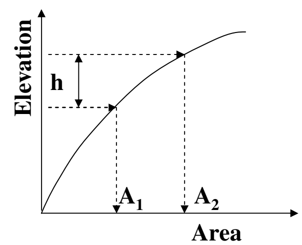
- Yield from a reservoir: the water amount that can be withdrawn from a reservoir in a specified period of time.
- Safe yield (firm yield): the maximum water volume can be supplied in a specified period of time during critical period (dry season).
- Secondary yield: the water volume that is available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

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



Surface water storage

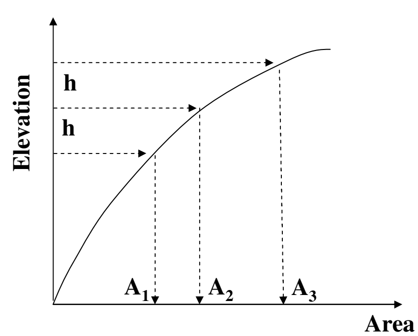
Storage capacity of existed reservoir:

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

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

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

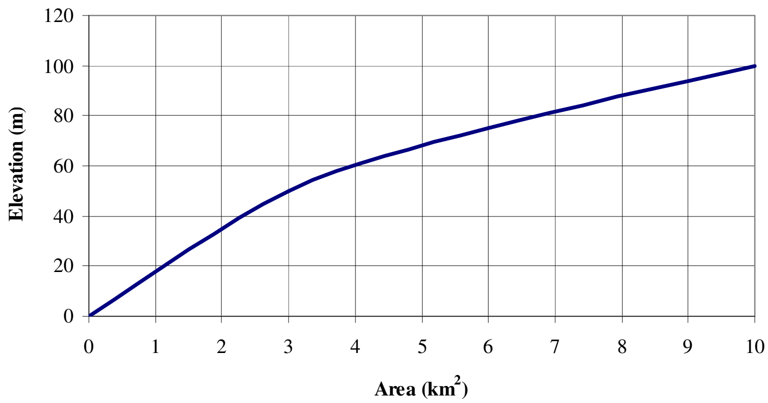
$$V = \Delta V_1 + \Delta V_2 + ...$$



Surface water storage

Ex:

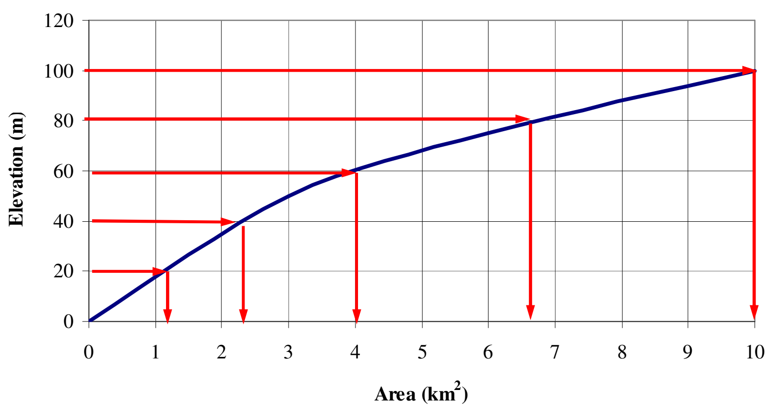
From the given elevation-area curve find the total storage volume (*V*) of an existed reservoir.



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:

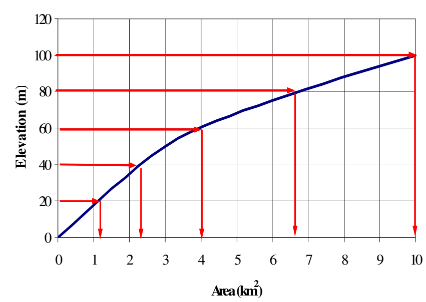
$$V = \Delta V_1 + \Delta V_2 + ...$$

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

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

$$=384 m.km^2$$

$$=384 Mm^3$$



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:

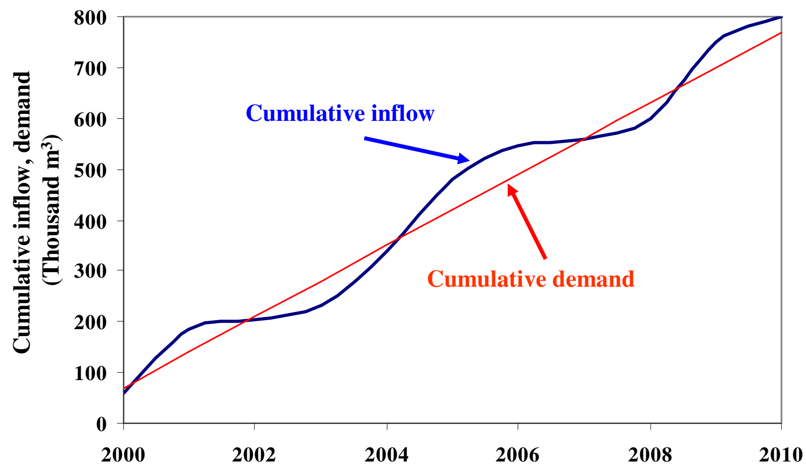
Step1: Calculate the cumulative inflows and cumulative demand.

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:

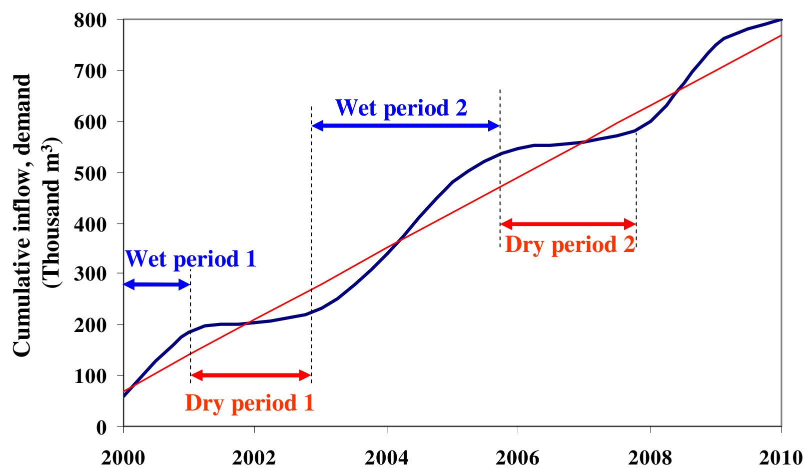
Step2: Plot the cumulative inflows and cumulative demand.



Surface water storage

Soln:

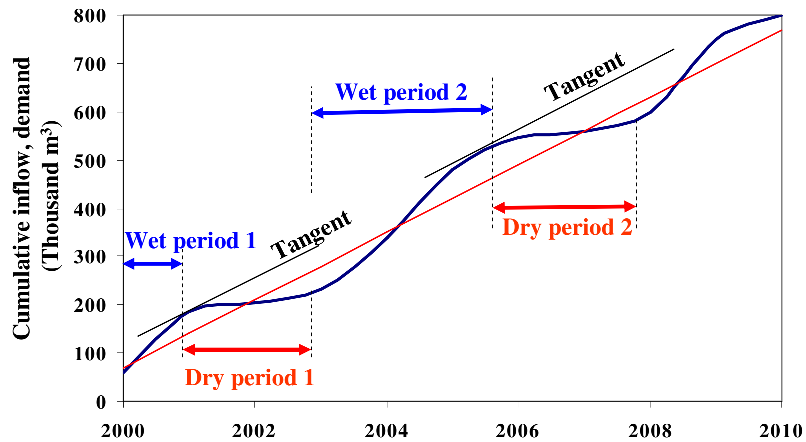
Step3: Locate dry and wet periods.



Surface water storage

Soln:

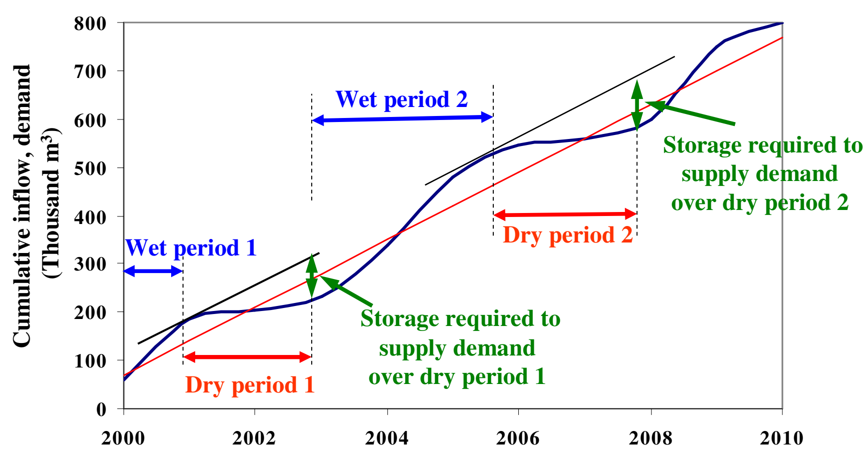
Step4: Construct tangents (parallel to demand) at the beginning of dry periods.



Surface water storage

Soln:

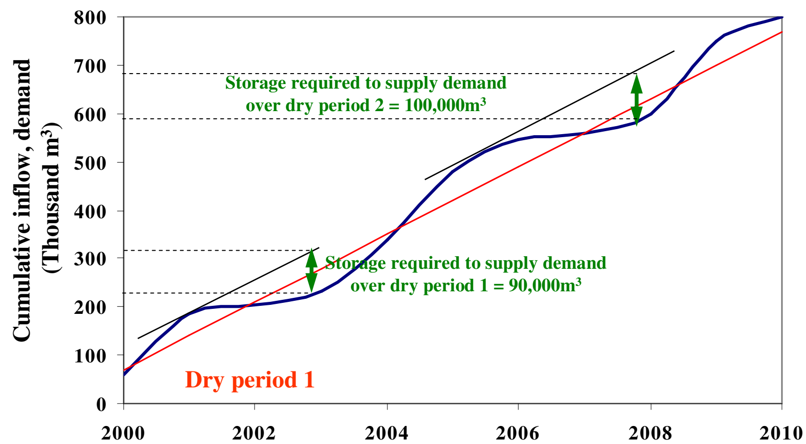
Step5: Find the storage required to supply the demand over the dry period.



Surface water storage

Soln:

Step6: Find the critical (maximum) storage required to supply the demand over the critical dry period. Storage = 100,000m³.



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 $111000 m^3$ which the reservoir active storage.

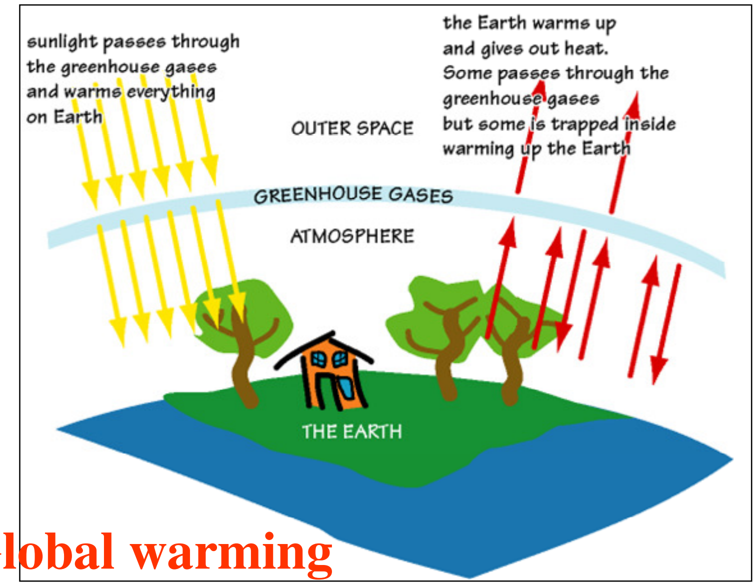
Surface water storage

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