Problem solving in engineering hydrology

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Preface

Engineering hydrology books, manuscripts and text material are abundant addressing perceptions, fundamentals, methods, models, designs and associated scientific concepts. However, rare are the books that deal with problem solving and practical complications in the field of engineering hydrology.

This book has been written to tackle material described in the 2-credit hour course of “Engineering Hydrology, ENVEN 431” given during the first semester for Junior Engineering students of the department of environmental engineering of the College Of Engineering at Dammam University as well as a 3-credit course Hydraulics and Hydrology, BEC 208 offered in the second year for Bachelor of Civil Engineering students at the Infrastructure University Kuala Lumpur. The named courses contents encompassed: Hydrologic cycle, precipitation and water losses. Catchment's characteristics and runoff processes. Flood estimation and control. Hydrograph analysis. Flood & reservoir routing. Groundwater occurrence, distribution, movement, exploration and recharge, well hydraulics and design, interaction of ground and surface water. Differential equations of groundwater flow. Darcy Law, solutions of the steady and unsteady flow, differential equations for confined and unconfined flows. Pumping test design. Groundwater models, leaky aquifers. Saltwater intrusion.

The book also covered the course contents of the subject “Hydrology and water gauging” CIVL 561 offered for the fifth year students of the department of civil engineering of Sudan University for Science and Technology. This particular course covered: Elements of hydrology. Precipitation. Surface runoff. Evaporation and evapotranspiration. Infiltration and groundwater flow. Hydrological measurement networks. Hydrograph. Flood routing.

Likewise, the book covered “hydrology” Course contents offered at the civil engineering department of the college of engineering at United Arab Emirates University.

The book also covered material subject dealt with while teaching the course in “hydrology” at School of Engineering and Technology Infrastructure, Kuala Lumpur Infrastructure University College.

Objectives of the book are meant to fulfill the main learning outcomes for students registered in named courses, which covered the following:

- Solving problems in hydrology and making decisions about hydrologic issues that involve uncertainty in data, scant/incomplete data, and the variability of natural materials.
- Designing a field experiment to address a hydrologic question.
- Evaluating data collection practices in terms of ethics.
- Interpret basic hydrological processes such as groundwater flow, water quality issues, water balance and budget at a specific site at local and regional scales based on available geological maps and data sets.
- Conceptualizing hydrogeology of a particular area in three dimensions and be able to predict the effects on a system when changes are imposed on it.

Learning outcomes are expected to include the following:

- Overview of essential concepts encountered in hydrological systems.
- Developing a sound understanding of concepts as well as a strong foundation for their application to real-world, in-the-field problem solving.
- Acquisition of knowledge by learning new concepts, and properties and characteristics of water.
- Cognitive skills through thinking, problem solving and use of experimental work and inferences
- Numerical skills through application of knowledge in basic mathematics and supply issues.
- Student becomes responsible for their own learning through solution of assignments, laboratory exercises and report writing.

Knowledge to be acquired from the course is expected to incorporate:

- Use real world data to develop a water budget for unfamiliar basins.
- Interpret groundwater resources data and correlate the geology with the groundwater regime.
- Evaluate ways in which water influences various geologic processes
- Identify interconnections in hydrological systems and predict changes.
- Predications of hydrological terms influencing the hydrological cycle.
- Collection of data, analysis and interpretation

Cognitive skills to be developed are expected to incorporate the following:

- Capturing ability of reasonable scientific judgment and concepts of appropriate decision making.
- Students will be able to apply the knowledge of hydrology that they have learnt in this course in practical environmental engineering domain.
- Students should be able to design and apply necessary procedures and precautions to produce durable hydro logical systems.

The majority of incorporated problems within the book represent examination problems that were given by the author to students at University of United Arab Emirates (UAE), Sudan University for Science and Technology (SUST), University of Dammam (UoD) and Infrastructure University Kuala Lumpur (IUKL). This is to expose students to different and design constraints and prevailing settings.

"Problem solving in engineering hydrology" is primarily proposed as an addition and a supplementary guide to fundamentals of engineering hydrology. Nevertheless, it can be sourced as a standalone problem solving text in engineering hydrology. The book targets university students and candidates taking first degree courses in any relevant engineering field or related area. The document is valued to have esteemed benefits to postgraduate students and professional engineers and hydrologists. Likewise, it is expected that the book will stimulate problem solving learning and quicken self-teaching. By writing such a script it is hoped that the included worked examples and problems will guarantee that the booklet is a precious asset to student-centered learning. To achieve such objectives immense care was paid to offer solutions to selected problems in a well-defined, clear and discrete layout exercising step-by-step procedure and clarification of the related solution employing vital procedures, methods, approaches, equations, data, figures and calculations.

The authors acknowledge support, inspiration and encouragement from many students, colleagues, friends, institutions and publishers. The authors salute the motivation and stimulus help offered to them by Dean Dr. Abdul-Rahman ben Salih Hariri, Dean College of Engineering of University of Dammam.. Thanks are also extended to Miss Azlinda binti Saadon from the Faculty of Civil Engineering at The Infrastructure University Kuala Lumpur for her cooperation and support. Special and sincere vote of thanks would go to Mr. Mugbil ben Abdullah Al-Ruwais the director of Dammam University Press and his supreme staff for their patience, dedication and orderly typing of the book

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Abbreviations, notations, symbols and terminology used in the book

A = Area, Area of groundwater basin normal to direction of water flow, Drainage area, Area of catchment basin (m^2, km^2, ha).

A = Cross-sectional area
A_i = Area of polygon surrounding station number i, located in its middle, m^2.
a = An exponent varying with surface roughness and stability of the atmosphere.
a = Index of surface connected porosity.
a, b, c = Hydraulic monitoring (gauging) stations to measure rainfall.
a = Rain slope constant.
a = Artificial recharge or loss of irrigation.
a and b = Constants.
a = Height (m) between zero on the gauge and the elevation of zero flow.
B = Heat exchange between soil and surface.
B = Stream roughness factor.
b = An empirical constant.
C = Coefficient representing the ratio of runoff to rainfall.
C = An empirical constant, Constant.
C = Coefficient controlling rate of decrease of loss-rate function.
C = Rational coefficient of surface flow.
C = Weight of salt solution passing sampling point per second.
C = Chezy roughness coefficient
C_2 = Weight of salt passing sampling point per second.
C_b = Concentration of tracer element in the river at start of injection.
C_i = Concentration of injected tracer element (within the stream).
C_m = Concentration of tracer component at measurement point (at equilibrium).
C_p = Specific heat of air at constant pressure.
C_t = Coefficient depending on units of drainage basin characteristics.
C_1 = Weight of concentrated solution added per second.
c, n = Locality constants.
c_p = Constant.
D = Distance from ocean, m.
D = Discharge from stage, m.
D = Rate on outflow, m^3/s.
D_x = Time period selected, m/s.
d = Surface-layer depth.
dh/dt = Change in stage during measurement, m/s.
dP = Pressure change with temperature, Pa.
dS/dt = Time rate of change of storage.
E = Amount of evaporation.
E = Evaporation from surface of river basin.
E = Evapotranspiration.

E = Amount of evaporation during a month, mm, inches.
E = Actual vapor pressure, mmHg.
E = Exponent, constant.
E = Actual vapor pressure of air at temp t.
EV = Total evaporation from soil and plants for specified time period.
EV = Evaporation, cm.
E_a = Evaporation from the earth, and from storage in low-lying areas.
E_a = Open water evaporation per unit time, mm/day.
E_a = Evaporation, mm/day.
E_a = Aerodynamic term.
E_b = Net energy lost by body of water through exchange of long wave radiation between atmosphere and body of water.
E_e = Energy utilized for evaporation.
E_h = Energy conducted from body of water to atmosphere as sensible heat.
E_o = Evaporation, mm/day.
E_o = Evaporation of lake, mm/day.
E_q = Increase in stored energy in the body of water.
E_r = Reflected solar radiation.
E_s = Solar radiation incident to water surface.
E_s = Saturated vapor pressure.
E_T = Evaporation from open surface of water (or equivalent in heat energy).
E_T= Evaporation rate.
E_v = Net energy adverted into the body of water.
E_w = Saturation vapor pressure at temp t_w of surface water of lake, mmHg.
e = Median value for vapor pressure, mbar.
e = Vapor pressure.
e = Base of natural logarithms.
e = Actual vapor pressure.
e = Actual vapor pressure at a defined height above surface.
e = Vapor pressure of air (monthly average), inches Hg.
e = Natural algorithm base.
e_s = Median value for saturation pressure, mbar.
e_a = Vapor pressure of air, mbar.
e_s = Saturation vapor pressure.
e_s = Saturated vapor pressure (mbar) when temperature is T_w
e_s = Saturated vapor pressure at surface temperature.
e_s = Saturation flexibility at surface, mm Hg.
e_s - e = d, = Lack of saturation Millbar.
e_w = Partial pressure of the gas for wet bulb temperature.
e_s = Saturation vapor pressure of air when temperature (t) ° C, mbar, mm Hg.
e_s = Saturation vapor pressure (monthly average), inches Hg.
e_2 = Vapor flexibility at a height of 2 meters.
F = Leakage.
F = Rate of mass infiltration at time t.

F = Total infiltration.
f (u) = A function in terms of wind speed at a some standard height.
f = Infiltration capacity (percolation) for time t.
f_c = Constant rate of infiltration after long wetting.
f_o = Initial infiltration capacity.
f_c = Final infiltration capacity = apparent saturated conductivity.
f = Natural recharge (rainfall – transpiration, surface runoff & infiltration).
F = Loss rate , mm per hour.
f = Possible head loss.
GI = Growth index of crop, percent of maturity.
H = Ponding depth.
H = Equivalent evaporation of total radiation on surface of plants.
H = Depth of confined aquifer
H = Depth of groundwater basin (m)
H = Saturated thickness of aquifer, m
H = Difference in elevation between two points after subtracting projections, feet.
h = Relative humidity, %
h = Depth below original water level.
h = Stage (gauge height).
I = Surface inflow.
I = Input (volume /time).
I = Part obstructed or trapped from rainfall.
I = Average intensity of rainfall, mm/hr.
I = Rainfall intensity, cm/hour.
I = Inflow to reach.
I = Rate of inflow, m^3/s.
I_t = Index value at t days later, mm.
I_o = Initial value to the index, mm.
i = Rainfall intensity, in or mm per hour.
i = Groundwater flow through area under consideration.
i = Hydraulic gradient.
K = Dimensionless constant.
K= Coefficient, storage constant (s), slope of relationship of storage-weighted discharge relation.
K_o = Loss coefficient at start of storm.
K_s = Effective hydraulic conductivity.
k = A recession constant.
k = Empirical constant for rate of decrease in infiltration capacity.
k = Proportionality factor, coefficient of permeability, or hydraulic conductivity (has dimensions of velocity).
k = Coefficient of permeability of the aquifer, m/s.
k = Constant of proportionality = reciprocal of slope of storage curve.
L = Latent heat of evaporation.
L = Latent heat per mole of changing state of water.
L = Specific heat of the vapor.
L = Latent heat of evaporation of water.

L = Accumulated loss during the storm, in or mm.
l = Distance in direction of stream line.
L = Depth to wetting front.
L = Maximum distance to entry point.
L = Length of stream, km.
L = Length from remotest point in basin to the outlet.
L = Main stream distance from outlet to divide.
l_{ca} = Stream distance from outlet to point opposite to basin centroid.
M_o = Average annual flow, m^3/s.
mcs = Water content at saturation that equals porosity (water content at residual air saturation).
mc = Water content at any instant.
N = Normal annual rainfall, mm.
N = Occurrence frequency, usually estimated once every N years = 10/n.
N = Net water infiltration rate resulting from rainfall.
N = Days of the month.
n = Number of days of the month (days of freezing not counted).
n = Number of occurrences in 10 years.
n = Retain coefficient equivalent to coefficient of friction.
n = Number of stations.
n/D = Cloudness ratio.
ne = Effective porosity, dimensionless.
O = Output, volume/time.
o = Groundwater outside borders of region.
P = Total pressure of humid air.
P '= Pressure of dry air.
P = Precipitation during a specific time period, year water.
P = Amount of rainfall, mm.
P = Amount of precipitation (rainfall).
P = Rainfall.
P = Total storm rainfall.
P = Atmospheric pressure, mbar.
P_e = Net rain representing portion of rainfall that reaches water courses for direct surface runoff.
P '= Decrease in rain.
P_x = Missing measurement or inaccurate record from station x, mm.
P_{av} = Arithmetic mean of rain, mm.
P_i = Amount of rainfall in station I, mm.
P_{mean} = Average rainfall in the region, mm.
P_i = Record of rainfall in station I, mm.
$\bar{P}$ = Average rainfall depth over the area.
P = Point rainfall depth measured at centre of the area.
Q = Total runoff (surface and ground) in basin during allotted time.
Q = Flow rate, flow
Q = Maximum rate of runoff, m3/s.

O = Surface outflow.
Q = Water flow rate.
Q = Total storm (surface) runoff.
Q = Steady state discharge from well
Q = Discharge as a function of time t, which changes from time t_1 to time t_2
Q_i = Average mean daily flow during a month i.
Q = Average annual flow.
Q = Peak discharge estimation expected to occur after heavy rains in the catchment basin, L/s.
Q = River flow.
Q_p = Discharge by probability of P , m^3/s.
Qa = Actual discharge (measured), m^3/s
Q = Steady state discharge (discharge from rating curve).
Q_t = Discharge at end of time t.
Q_a = Discharge at start of period.
Q = Discharge.
q = Flow rate of injected tracer to stream.
q = Ground water production from wells and disposal channels.
q = Flow in aquifer per unit width of basin, $m^3/s/m$.
q_p = Peak flow.
R = Bowen ratio.
R = Gas constant, L×atmosphere/K.
R = Radiation balance
R_A = Agot's value of solar radiation arriving at atmosphere.
R_1 and R_2 = Working values, representing indices of storage.
r = Addition and increase of underground water due to egress of surface water.
r = Distance from well.
r_a= Aerodynamics resistance.
r_H = Hydraulic radius, m.
r_s = Net physiological resistance.
S = Slope of energy line.
S = Storage coefficient.
S = Change in storage = Total precipitation over collecting surface.
S = Effective surface retention.
S = Volume of water, storage.
S = Stored volume of surface and ground for specified time period.
S = Change in reserved moisture in river basin.
S = Available storage in surface layer.
S = Absolute slope, m/m.
S = Stream slope, %
S = Steady stage energy gradient at the time of measurement, m/m.
S = Storage, m^3
S_d = Storage in low-lying areas.
S_f = Suction (capillary) head at the wetting front.

s = Increase in storage.
s = Drawdown.
T = Absolute temperature, K.
T = Transmissivity, m^2/day.
T = Number of seconds in a year (86400 = the number of seconds per day).
T = Base time (time from beginning and end of the flood).
T = Tme base for unit hydrograph, day.
T_r = Residence time.
Tw = Water surface temperature, ^oC.
Ta = Air temperature, ^oC.
t = Average dry temperature of the month, ° C.
t = Dry temperature.
t = Rainfall duration, minutes.
t = Time, day.
t_p = Basin lag, hours.
t_p = Time lag in the basin, hours.
t_c = Time of entry, minutes.
t_r = Unit rain period (duration of unit hydrograph).
t_{pR} = Basin lag for a storm of duration t_R, hours.
t_w = Temperature of wet bulb temperature (humid temperature).
(t*) = Gamma inverse function for storm time.
tf = Total time during which rainfall intensity is greater than W.
t_o = Temperature of evaporation surface.
t_2 = Air temperature at a height of 2 meters.
V = Amount of moisture leaking for the period.
V = Volume of runoff.
V_f = Final molar volume for states of liquidity and gaseous.
V_i = Primary molar volume for states of liquidity and gaseous.
v = Flow velocity, m/s.
v = Wind speed, m/w.
v = Velocity of water flow (= specific velocity).
v' = Average pore velocity (actual or real velocity), m/s.
v = Relative (specific) velocity, m/s.
v = Specific velocity in the horizontal x direction, m.
V_s = Surface velocity.
V_{av} = Average velocity in a section of flow.
U = Groundwater inflows and outflows.
U – O = Quantity of flow in river (surface and underground).
U = Velocity of flood wave (flood wave celerity), m/s
u = Wind speed, miles/hour.
u = Wind speed in the region at height z_o, m /s.
u_o = Wind speed at least height (at anemometer) z_o, , m/s.
u_1 = Wind speed at a height of 1 meter, m/s.
u_2 = Median value of wind speed at a height of 2 m above water surface, m/s.
u_2 = Wind speed at a height of 2 meters, m/s.

u_2 = Wind speed at height of 2 m, m/s.
u_6 = Wind velocity at a height of 6 meters above the surface, m/s.

u (T, t) = Ordinate of the T-hour unit hydrograph derived from those of the t hour unit hydrograph.

W = W–index = Average infiltration rate during the time rainfall intensity exceeds the capacity rate.

W = Upper limit of the value of soil humidity that do not move by capillary action from the soil to the surface, %

W_v = Volumetric soil moisture, %

X = Dimensionless constant for a certain river reach, dimensionless.
x = Distance along flow line, m.

x, k = Constants derived from observed portion of curve.
y_o, y_n = Flows at beginning and end of flood, respectively.
Y_1, y_3 = Odd flows.
Y_4, y_6 = Even flows.
z = Height, m.
z_o = Height of anemometer (minimum height), m
α = Constant.
α = Coefficient of aquifer
γ = Psychrometer constant.
γ = Proportionality factor.
γ = Psychrometer constant fixed device to measure humidity.
Δh = Change in humidity for the period.
Δt = Difference between evaporation surface and air temperature.
ρ = Density of water
θ = Psychometric difference, ° C.
Δ =-Slope of vapor pressure curve at t = tan α
$\Delta s/\Delta t$ = Rate of change in reach storage with respect to time.
Δt = Routing Period.
ρ_a = Air density.
ρ_w = Density of water.
ϕ = Head loss over an appropriate base level.
ϕ = Potential head loss, m.

Chapter One

Meteorological data (Humidity, temperature, radiation and wind)

1.1 Humidity

Maximum value of water vapor that can exit in any one space is a function of temperature, and is practically independent of the coexistence of other gases. When maximum amount of water vapor (for a given temperature) is contained in a given space, the space is said to be saturated. The pressure exerted by a vapor in a saturated space is called “saturation vapor pressure. “

1.2 Relative humidity

Relative humidity is the percentage of actual vapor pressure to saturation vapor pressure. It is the ratio of amount of moisture in a given space to the amount a space could contain if saturated.

1.3 Dew point

Dew point denotes the temperature at which space becomes saturated when air is cooled under constant pressure and with constant water vapor pressure. Also dew point is the temperature having a saturation vapor pressure, e_s equal to the existing vapor pressure, e.

Example 1.1

An air mass is at a temperature of 20° C with relative humidity of 75%. Using the following equation $h = 100\, x \frac{e}{e_S}$ find: saturation vapor pressure, actual vapor pressure, the deficit in saturation and dew point. (B.Sc., DU, 2011)

Solution

1) Data given: T = 20° C, h = 75 %
2) Find from tables (see annex) the value of saturated vapor pressure at a temperature of 20° C,
   Value of saturated vapor pressure e_s = 17.53 mm Hg
3) Substitute data in humidity equation:

$$h = 100\, x \frac{e}{e_S}$$

Where:
h = Relative humidity, %, which describes the ability of air to absorb additional moisture at a given temperature.
e = Actual vapor pressure
e_s = Saturation vapor pressure. (Numerical value of e_s are to be found from tables).

h = 100 * e/e_s, find real vapor pressure:
75 = 100 × e ÷ 17.53
Real vapor pressure e = 13.1475 mm Hg.

4) Find saturation deficit as follows:
   Saturation deficit: $e - e_s = 17.53 - 13.1475 = 4.3825$ mm Hg.
5) Find dew point as the temperature at which the values of e_s and e are equal.
   Since: $e_s = 13.1475$ mm Hg, then one can find the temperature, and then the dew point can be found from tables and for the value of $e_s = 13.1475$, dew point = 15.4 ^{o} C.

1.4 Water Budget

Hydrological cycle is a very complex series of processes. Nonetheless, under certain well-defined conditions, the response of a watershed to rainfall, infiltration, and evaporation can be calculated if simple assumptions can be made.

Example 1.2

For a given month, a 121 ha lake has 0.43 m^3/s of inflow, 0.37 m^3/s of outflow, and the total storage increase of 1.97 ha-m. A USGS gauge next to the lake recorded a total of 3.3 cm precipitation for the lake for the month. Assuming that infiltration loss is insignificant for the lake, determine the evaporation loss, in cm over the lake for the month.

Solution

Given, P = 3.3 cm, I = 0.43 m^3/s, Q = 0.37 m^3/s, S = 1.97 ha-m, Area, A = 121 ha

Solving the water balance for Inflow, I and Outflow, O in a lake gives, for evaporation, E ;

$$\text{Inflow, I} \quad = \quad \frac{\left(0.43\ \frac{m^3}{s}\right)\left(1\ month \times \frac{30\ day}{1\ month}\right)\left(\frac{24\ hour}{1\ day}\right)\left(\frac{3600\ s}{1\ hour}\right)}{(121\ ha)\left(\frac{10\ 000\ m^2}{1\ ha}\right)}$$

Inflow, I = 0.92 m = 92 cm

$$\text{Outflow, Q} \ = \ \frac{\left(0.37\ \frac{m^3}{s}\right)\left(1\ month \times \frac{30\ day}{1\ month}\right)\left(\frac{24\ hour}{1\ day}\right)\left(\frac{3600\ s}{1\ hour}\right)}{(121\ ha)\left(\frac{10\ 000\ m^2}{1\ ha}\right)}$$

Outflow, Q = 0.79 m = 79 cm

Additional data :

Direct Precipitation, P = 3.3 cm

$$\text{Storage, S} = \frac{1.97\ ha.m}{121\ ha} = 0.0163\ \text{m} = 1.63\text{cm}$$

From water budget equation,

$$P - R - G - E - T \quad = \quad \Delta S$$

In this case,

$I + P - Q - E = \Delta S$

Therefore,

Evaporation, E:

$E = I + P - Q - \Delta S$

$E = 92 + 3.3 - 79 - 1.63$

$E = 14.67$ cm

EXAMPLE 1.3

At a particular time, the storage in a river reach is 60 x 10^3 m^3. At that time, the inflow into the reach is 10 m^3/s and the outflow is 16 m^3/s. after two hours, the inflow and the outflow are 18 m^3/s and 20 m^3/s respectively. Determine the change in storage during two hours period and the storage volume after two hours.

Solution

Given, I_1 = 10 m^3/s

I_2 = 18 m^3/s

O_1 = 16 m^3/s

O_2 = 20 m^3/s

S_1 = 60 x 10^3 m^3

Δt = 2 hours x 60 min x 60 s = 7200 s

1) Change in storage, ΔS during two hours :

I - O = ΔS

$$\left(\frac{I_1 + I_2}{2}\right) - \left(\frac{O_1 + O_2}{2}\right) = \frac{\Delta S}{t}$$

$$\left(\frac{10 + 18}{2}\right) - \left(\frac{16 + 20}{2}\right) = \frac{\Delta S}{t}$$

Therefore,

$$\frac{\Delta S}{t} = -4\,\frac{m^3}{s}$$

$$\Delta S = -4\,\frac{m^3}{s} \times 7200\ s$$

$$\Delta S = -28\,800\ m^3$$

2) Storage Volume after two hours, S_2 :

$\Delta S = S_2 - S_1$

Rearrange,

$S_2 = \Delta S + S_1$

S_2 = - 28 800 + 60 x 10^3

S_2 = 31 200 m^3

1.5 Wind

Wind denotes air flowing nearly horizontally. Winds are mainly the result of horizontal differences in pressure. In absence of other factors tending to influence wind, it should be expected that its direction would be from areas of high pressure towards areas of low pressure and that its speed would vary with the pressure gradient.

Example 1.4

At a given site, a long-term wind speed record is available for measurements at heights of 10m and 15m above the ground. For certain calculations of evaporation the speed at 2m is required, so it is desired to extend the long-term record to the 2m level. For one set of data the speeds at 10 and 15 m were 7.68 and 8.11 m/s respectively (B.Sc., DU, 2013).

i. What is the value of the exponent relating the two speeds and elevations?

ii. What speed would you predict for the 2 m level?

$$\frac{u}{u_o} = \left(\frac{z}{z_o}\right)^a$$

Solution

- Data given: z_1 = 10 m, z_2 = 15, u_{10} = 7.68 m/s, u_{15} = 8.22 m/s. Required: a, u_2
- Use equation $\frac{u}{u_o} = \left(\frac{z}{z_o}\right)^a$ to determine the constant a:

  Where:

  u = Wind speed in the region at height zo m /s

  uo = Wind speed at least height (at anemometer) zo . m/s

  zo = Height of anemometer (minimum height), m

  a = An exponent varying with surface roughness and stability of the atmosphere, (usually ranging between 0.1 to 0.6 in the surface boundary layer).

$$\frac{7.68}{8.11} = \left(\frac{10}{15}\right)^a$$

Or: a*Log (10/15) = Log (7.68/8.11) which yields a = 0.134

- Use equation $\frac{u_{10}}{u_2} = \left(\frac{z_{10}}{z_2}\right)^a$ $\quad \frac{7.68}{u_2} = \left(\frac{10}{2}\right)^{0.134}$

Which yields: u_2 = 6.19 m/s

1.6 Theoretical Exercises

1) Write briefly about <u>three</u> of the following: (B.Sc., UAE, 1989).
   a) The **hydrologic cycle** and the principal influences that prevent its phases from repeating themselves in an identical fashion from year to year.
   b) Factors that influence **evaporation**. Explain briefly how each factor affects the rate and time of occurrence of evaporation.
   c) Types of **precipitation**. On what category would you place rain rainfall at El-Ain.
   d) Infiltration indexes and their importance.
2) Show how the following relationship can be used to find the **wind** speed from the height above the ground. (B.Sc., DU, 2011)

$$\frac{u}{u_o} = \left(\frac{z}{z_o}\right)^a$$

3) State Buys **Ballot** law (B.Sc., DU, 2013).

   Solution

   "Low-pressure zone in the northern part of the globe lies north of the viewer who stands giving his back to the wind, and it is located on his right side in the southern part of the globe, as a result of the impact of the earth's rotation".
4) It is necessary to specify height above sea level when doing any measurement of **wind** due to surface friction factors and water surfaces through which wind is blowing. The

relationship between wind speed and height can be found from the following relationship. Define the shown terms. (B.Sc., DU, 2012)

$$\frac{u}{u_o} = \left(\frac{z}{z_o}\right)^a$$

5) Define and explain: **Dew point, Ballton's** law, Orographic **precipitation** and an isohyetal map. (B.Sc., UAE, 1989, B.Sc., DU, 2012)).

Solution

- Is the temperature at which $e_s = e$.
- If an observer stands with his back to the wind, the lower pressure is on his left in the northern hemisphere and his right in the southern hemisphere.
- Results from mechanical lifting over mountain barriers. Most is deposited on the windward slopes.
- Map showing lines of equal rainfall amount.

6) Define: **relative humidity, dew point** and **wind** (B.Sc., DU, 2012).

Solution

Relative humidity is the percentage of actual vapor pressure to saturation vapor pressure or is the ratio of amount of moisture in a given space to the amount a space could contain if saturated.

Dew point: Denotes the temperature at which space becomes saturated when air is cooled under constant pressure and with constant water vapor pressure. Also it is the temperature having a saturation vapor pressure, e_s equal to the existing vapor pressure, e.

Wind: denotes air flowing nearly horizontally.

7) What is **hydrology**? What are the benefits of this science in practical life?
8) Indicate general factors affecting **climate**, and methods of measurement. Illustrate your answer with appropriate sketches.
9) Mention advantages of measuring **temperature**.
10) What is meant by "areas of low and high **pressure**"? How are they detected?.
11) Write a detailed report on each of the following: moisture, **relative humidity, water vapor pressure**, and **dew point**.
12) Outline marked differences between methods of measuring **humidity**.
13) What is the benefit of measuring solar **radiation**?
14) Explain ways of **cloud** formation.
15) Explain water vapor **condensation** in air. What are the benefits of the process?
16) What factors affect **evaporation**?
17) Write a detailed report on instruments for measuring **evaporation**.
18) How does both surface water and groundwater affect **evaporation**?
19) Mention different types of **precipitation** and their presence in practice.
20) How **precipitation** is measured? Compare its measurement devices.
21) What are elements of a hydrological **Meteorological station**?

1.7 Problem solving in meteorological data

Pressure

1) A hill is of height of 4000 meters and of rising dry air temperature of 14.8 degrees Celsius. Condensation occurs at a height of 2000 meters. Calculate the **pressure** and saturation drop. Find air temperature when it reaches the top of the mountain and its temperature when it reaches top of hill and its temperature when it returns to the bottom.

Vapor pressure

2) An air mass is at a temperature of 18^o C with relative humidity of 80 %. Using the following equation $h = 100\,x\,\frac{e}{e_s}$ find: (B.Sc., DU, 2012)
   i. Saturation **vapor pressure**.
   ii. Actual vapor pressure in mm Hg, m bar, and Pa
   iii. The deficit in saturation
   iv. Dew point.

Solution

1) data: T = 18^o C, h = 80 %
2) Find from tables the value of saturated vapor pressure at a temperature of 18^o C, value of saturated vapor pressure e_s = 15.46 mm Hg
3) Substitute data in h = 100 * e / e_s find real vapor pressure:
   80 = 100 × e ÷ 15.46
   Actual or real vapor pressure e = 12.386 mm Hg = 12.386*1.33 = 16.45 m bar = 16.45*10^2 = 1.6*10^3 N/m^2 = 1.6 kPa
4) Find saturation deficit as follows:
   Saturation deficit: e - e_s = 15.46 - 12.386 = 3.07 mm Hg.
5) Find dew point as the temperature at which the values of e_s and e are equal.
   Since: e_s = 12.386 mm Hg, then one can find the temperature, and then the dew point can be found from tables and for the value of e_s = 12.386 dew point = 13.2 ^{o} C.

3) An air mass is at a temperature of 24.5 ºC with relative humidity of 58%. Determine: (B.Sc., UAE, 1989).
   - Saturation **vapour pressure**.
   - Saturation deficit.
   - Actual vapour pressure (in mbar, mmHg, and Pa).
   - **Dew point**.

Solution

For a temperature of 24.5 ºC from table or figure

i] Saturation pressure e_s = 23.05 mmHg

ii] Relative humidity, h = $100\,\frac{e}{e_s}$

$$\therefore 58 = 100\,\frac{e}{23.05}$$

$$\therefore e = 13.37\ mmHg$$

Saturation deficit = e_s – e = 23.05 – 13.37 = 9.68 mmHg

iii] Actual vapour pressure = 13.37 mmHg = 13.37×1.33 = 1778 mbar = 1778×10^2 = 1.78 kN/m^2 = 1.78 kPa.

iv] Dew point is the temperature at which e = e_s

∴ e_s = 13.37 mmHg and from table:

Dew point = 15.7 ºC

4) A mass of air is at a temperature of 22°C and relative humidity of 81%. Find: saturated vapor pressure, real vapor pressure, saturation deficit, and dew point (Ans. 19.82, 16.05, 3.77mmHg, 18.6°C).
5) An air mass is at a temperature of 28° C with relative humidity of 70%. Find:
   a) Saturation **vapor pressure**
   b) Actual vapor pressure in mbar and mm Hg
   c) Saturation deficit
   d) Dew point
   e) Wet-bulb temperature.
6) To a mass of air at a temperature of 20° C and relative humidity of 80%, find saturated vapor pressure, real vapor pressure, deficit in saturation, and dew point. What is the difference in your answer if the temperature changed to 25° C and relative humidity to 75%.
7) An air mass is at a temperature of 20° C with relative humidity of 75%. Using the following equation $h = 100 \times \frac{e}{es}$
   i. Saturation **vapor pressure**
   ii. Actual vapor pressure
   iii. The deficit in saturation
   iv. Dew point

   (ans. 22.53 mm Hg, 16.8975 mm Hg, 5.63 mm Hg, 19.4 ° C).

Wind

8) Anemometers at 2.5 m and 40 m on a tower record wind speeds of 2 and 5 m/s respectively. Compute **wind speeds** at 5 and 30 m. (B.Sc., DU, 2012)

   Solution

   b) $\frac{u}{u_o} = \left(\frac{z}{z_o}\right)^k$

   $$\frac{2}{5} = \left(\frac{2.5}{40}\right)^k$$

   $$k = 0.33$$

   $$u_5 = \frac{2}{\left(\frac{2.5}{5}\right)^{0.33}} = 2.51\ m/s$$

   $$u_{30} = \frac{2}{\left(\frac{2.5}{30}\right)^{0.33}} = 4.54\ m/s$$

9) At a given site, a long-term wind speed record is available for measurements at heights of 5 m and 10 m above the ground. For certain calculations of evaporation the speed at 2 m is required, so it is desired to extend the long-term record to the 2 m level. For one set of data the speeds at 5 and 10 m were 5.51 and 6.11 m/s respectively (B.Sc., DU, 2012).
   i. What is the value of the exponent relating the two speeds and elevations?
   ii. What **wind speed** would you predict for the 2 m level?

Solution

1. Data given: $z_1 = 5$ m, $z_2 = 10$, $u_5 = 5.51$ m/s, $u_{10} = 6.11$ m/s r.
2. Required: a, u_2

3. Use equation to determine the constant a:

$$\frac{u_5}{u_{10}} = \left(\frac{z_5}{z_{10}}\right)^a \qquad \frac{5.51}{6.11} = \left(\frac{5}{10}\right)^a$$

Or a Log 10/15 = Log 5.51/6.11 which yields a = 0.149

4. Use equation

$$\frac{u_5}{u_2} = \left(\frac{z_5}{2}\right)^a \qquad \frac{5.51}{u_2} = \left(\frac{5}{2}\right)^{0.149}$$

Which yields u_2 = 4.8 m/s

10) At a given site, a long-term wind speed record is available for measurements at heights of 5 m and 10 m above the ground. For certain calculations of evaporation the speed at 2 m is required, so it is desired to extend the long-term record to the 2 m level. For one set of data the speeds at 5 and 10 m were 5.11 and 5.61 m/s respectively. (B.Sc., DU, 2011)
    iii. What is the value of the exponent relating the two speeds and elevations?
    iv. What **speed** would you predict for the 2 m level?

Solution

1. Data given: z_1 = 5 m, z_2 = 10, u_{10} = 5.11 m/s, u_{15} = 5.61 m/s r.
2. Required: a, u_2
3. Use equation to determine the constant a:
   $U_{10}/u_{15} = (5/10)^a = 5.11/5.61$
   Or a Log 5/10 = Log 5.11/5.61 which yields a = 0.134677
4. Use equation $u_{10}/u_2 = 5.11/u_2 = (5/2)^{0.134667}$,
   Which yields U_2 = 4.51 m/s

11) Anemometers at 2m and 50m on a tower record wind speeds of 2 and 5 m/s respectively. Compute **wind speeds** at 5 and 30 m. (B.Sc., UAE, 1989).

Solution

$$\frac{u}{u_o} = \left(\frac{z}{z_o}\right)^k$$

$$\frac{2}{5} = \left(\frac{2}{50}\right)^k$$

$$0.04^k = 0.4 \quad \rightarrow \quad u_5 = 2.6\ m/s$$

$$u_{30} = \frac{2}{\left(\frac{2}{30}\right)^{0.285}} = 4.3\ m/s$$

12) Anemometers at 2.5 m and 40 m on a tower record wind speeds of 2 and 5 m/s respectively. Compute **wind speeds** at 5 and 30 m. (ans. 2.51, 4.54 m/s).
13) Anemometers at 2m and 50m on a tower record wind speeds of 2 and 5 m/s respectively. Compute **wind speeds** at 5 and 30 m. (ans. 2.6, 4.6 m/s).
14) Theoretical Wind speed is measured for two heights 3 and 4 meters and the following values were found 2.5 and 3 m/s, respectively. Find wind speed for a height of two meters.
15) Measured wind speed in a monitoring station for two heights 1 and 2 meters has shown the values of 1.6 and 2.2 m/s, respectively. Find **wind speed** at a height of two meters and ten meters.

Water budget

16) At a water elevation of 6391 ft, Kenyir Lake has a volume of 2, 939, 000 ac-ft, and a surface area, A of 48, 100 ac. Annual inputs to the lake include 8.0 in. of direct precipitation, runoff from gauged streams of 150, 000 ac-ft per year, and ungauged runoff and groundwater inflow of 37, 000 ac-ft per year. Evaporation is 45 inch. per year.
Make a **water budget** showing inputs, in ac-ft per year.
(*Note : 1 ac = 43, 560 ft^2, 1 cm = 0.394 in, 1 in = 0.083 ft)

Solution

Given, Water Elevation, EL = 6391 ft
Volume of lake, V = 2, 939, 000 ac-ft
Area, A = 48, 100 ac

1) Annual input, I to the lake :

a) Direct precipitation, P = 8 in / year

$$= (8\ in)\left(\frac{0.083\ ft}{1\ in}\right)(48,100\ ac)$$

= 31, 938.40 ac-ft / year

b) Runoff from gauged streams = 150, 000 ac-ft / year

c) Runoff from ungauged = 37, 000 ac-ft / year

Therefore,
Total annual input, I = 31, 938.40 + 150, 000 + 37, 000
= 218, 938.40 ac-ft / year.

2) Outflow, O :

a) Evaporation, E = 45 in / year

$$E = (45\ in)\left(\frac{0.083\ ft}{1\ in}\right)(48,100\ ac)$$

E = 179, 653.50 ac-ft / year

3) Water Budget :

$\Delta S = I - O$

$\Delta S = 218,938.40 - 179,653.50$

ΔS = 39, 284.90 ac-ft / year (positive)

Chapter Two

Precipitation

2.1 Precipitation

Precipitation denotes all kinds of rainfall on surface of earth from vapor in the atmosphere (most of humidity at a height of 8 km from the Earth's surface).

Table 2.1 Forms of precipitation [1,2, 10]

Form of precipitation	Rate of fall (mm/hr)
Light	2.5
moderate	2.8 – 7.6
Heavy	> 7.6

2.2 Interpolation of rainfall records

Sometimes records may be lost from the measuring or monitoring station for a specific day or several days because of the absence of station operator (observer) or because of instrumental failure or malfunction or damage in the recording devices, for any other reason. In order not to lose information, it is best to use an appropriate way to estimate the amount of rain in these days in calculating monthly and annual totals. Procedure for these estimates are based depending on simultaneous records for three stations close to and as evenly spaced around the station with missing records as possible. This station should be equi-distant from the three stations and the following conditions should be achieved:

- If the normal annual precipitation at each of the these stations is within ten percent of that of the station with missing records, a simple arithmetic average of the precipitation at the three stations is used for estimating missing record of the station.
- If the normal annual precipitation at any one of the three stations differs from that of the station with missing records by more than ten percent, the normal ratio method is used [15].

Example 2.1

1) Rain gauge X was out of operation for a month during which there was a storm. The rainfall amounts at three adjacent stations A, B, and C were 37, 42 and 49 mm. The average annual precipitation amounts for the gauges are X = 694, A = 726, B = 752 and C = 760 mm. Using the Arithmetic method, estimate the amount of rainfall for gauge X.

Stations	Amounts of precipitation (mm)	Normal Annual Precipitation (mm)
A	37	726
B	42	752
C	49	760
D	?	694

Solution

If

$N_x = 694$

Then 10% from 694 = $\frac{10}{100} \times 694 = 69.4\ mm$

Therefore, precipitation allowed = (694 – 69.4) ~ (694 + 69.4) mm

= 624.6 mm ~ 763.4 mm

Since all annual precipitations (726, 752 and 760) mm are within the ranges, **Arithmetic Method** can be applied :

$$P_x = \frac{1}{3}\{37+42+49\} = 42.7mm$$

Example 2.2

One of four monthly-read rain gauges on a catchment area develops a fault in a month when the other three gauges record 48, 58 and 69 mm respectively. If the average annual precipitation amounts of these three gauges are 741, 769 and 855 mm respectively and of the broken gauge 707 mm, estimate the missing monthly precipitation at the latter (B.Sc., DU, 2013).

Solution

$$P_x = \frac{\frac{N_x P_a}{N_a} + \frac{N_x P_b}{N_b} + \frac{N_x P_c}{N_c}}{3}$$

- Data: P_a = 48 mm, P_b = 58 mm, P_c = 69 mm, N_a = 741 mm, N_b = 769 mm, N_c = 855 mm, N_x = 707 mm.
- Find the value of rainfall during the storm at station (a) by using the following equation:

$$P_x = \frac{\frac{N_x P_a}{N_a} + \frac{N_x P_b}{N_b} + \frac{N_x P_c}{N_c}}{3} = \frac{\frac{707x48}{741} + \frac{707x58}{769} + \frac{707x69}{855}}{3} = 52\ mm$$

Example 2.3

The records of precipitation of hydraulic monitoring stations (x) in a rainy day are missing. The data indicate that the estimates of rainfall at three stations (b), (c) and (d) adjacent to the station (x) are equal to: 80, 70 and 60 mm, respectively. If the average annual rainfall at stations (a) and (b) and (c) and (d) is: 650, 240, 320 and 140 mm, respectively, find the value of rainfall during the rain storm in station (x) (B.Sc., DU, 2012) .

Solution

1. Data: Pb = 80 mm, Pc = 70 mm, Pd = 60 mm, Nx = 650 mm, Nb = 240 mm, Nc = 320 mm, Nd = 140 mm.
2. Find the value of rainfall during the storm at station (a) by using the following equation: Px = 212.5 mm

2.3) Methods used to find the height of rainfall

Methods used to find the height of rainfall Include: Arithmetic mean method, Thiessen polygon method and isohyets method.

Example 2.4

Using the data given below, estimate the average precipitation using Thiessen Polygon method.

Stations	Area (km^2)	Precipitation (mm)	Area x Precipitation ($km^2 \cdot mm$)
A	72	90	6 480
B	34	110	3 740
C	76	105	7 980
D	40	150	6 000
E	76	160	12 160
F	92	140	12 880
G	46	130	5 980
H	40	135	5 400
I	86	95	8 170
J	6	70	420
TOTAL	568	1 185	69 210

Solution

$$Average\quad Percipitation = \frac{\sum Polygon\ Area\ \ for\ each\ Station \times \Pr ecipitation}{\sum Total\ Polygon\ Area}$$

$$Average\quad Percipitation = \frac{69210}{568}$$

$$Average\quad Percipitation = 121.8mm$$

Example 2.5

The precipitation on a catchment in Dubai of area 95 km^2 is sampled in table (1). Determine the precipitation recorded by station number (7) if the mean precipitation, as computed by Thiessen method, amounts to 98mm. (B.Sc., UAE, 1989).

Rain gauge	Recorded rainfall, Feb. 1968 (mm)	Thiessen polygon on area (km^2)
1	84	4.0
2	90	4.0
3	120	10.0
4	86	5.1
5	87	15.1
6	76	30.6
7	X	6.2
8	131	20.0

Solution

a)

Rain gauge	Recorded rainfall, Feb. 1968 (mm)	Thiessen polygon on area (km^2)	Product
1	84	4.0	336
2	90	4.0	360
3	120	10.0	1200
4	86	5.1	438.6
5	87	15.1	1313.7
6	76	30.6	2325.6
7	X	6.2	6.2x
8	131	20.0	2620

$\sum A = 95$ $\sum AP = 8593.9 + 6.2x$

$$98 = \frac{8593.9 + 6.2x}{95}$$

$$\therefore x = \frac{716.1}{6.2} = 115.5mm$$

Example 2.6

Find area precipitation by isohyetal method for a certain catchment area given the following data (B.Sc., DU, 2012).

Isohyet, in	Area enclosed within basin boundary, sq. mile
6.8	
6	20
5	97
4	213
3	410
2	602
1.5	633

Solution

Isohyet, in Col. (1)	Area enclosed within basin boundary, sq. mile Col. (2)	Net area, sq. mile Col. (3) (b_n-b_{n-1})	Average precipitation Col. (4) (a1+a2)/2	Precipitation volume Col. (3)*Col. (4)
6.8				
6	20	20	(6.8+6)/2 = 6.4	128
5	97	97-20 = 77	5.5	423.5
4	213	213-97 = 116	4.5	522
3	410	410-213 = 197	3.5	689.5
2	602	602-410 =192	2.5	480
1.5	633	633-602 = 31	1.75	54.25
	Total area = 633			Total volume = 2297.25

P = 2297.25/633 = 3.63 in

Example 2.7

The following table shows rainfall observations taken for a certain area. Estimate the mean basin precipitation (B.Sc., DU, 2012) .

Table: Rainfall observations.

Isohyets (in)	Total area enclosed within basin boundary (ha)	Estimated mean precipitation between isohyets
> 6	50	6.3
> 5	120	5.5
> 4	250	4.7
> 3	450	3.6
> 2	780	2.7
> 1	999	1.4
< 1	1020	0.8

Solution

Determine corresponding net area as in table below:

Isohyets (in)	Total area enclosed within basin boundary (ha)	Corresponding net area	Estimated mean precipitation between isohyets
> 6	50	50	6.3
> 5	120	70	5.5
> 4	250	130	4.7
> 3	450	200	3.6
> 2	780	330	2.7
> 1	999	219	1.4
< 1	1020	21	0.8

$$n_i = \sum_{i=1}^{n} A_i \times \frac{p_{i-1}+p_i}{2} \Big/ \sum_{i=1}^{n} A_i = \frac{50\times6.3+70\times5.6+130\times4.7+200\times3.6+330\times2.7+219\times1.4+21*0.8}{50+70+130+200+330+219+21} = 11.06\ ''$$

Example 2.8

The following rainfall observations were taken for a certain area: (B.Sc., UAE, 1989).

Isohyets (in)	Total area enclosed within basin boundary (ha)	Estimated mean precipitation between isohyets
> 6	40	6.2
> 5	110	5.5
> 4	236	4.5
> 3	430	3.5
> 2	772	2.5
> 1	990	1.5
< 1	1010	0.9

Estimate the mean basin precipitation

Solution

Determine corresponding net area as presented in the following table:

Isohyets (in)	Total area enclosed within basin boundary (ha)	Corresponding net area	Estimated mean precipitation between isohyets
> 6	40	40	6.2
> 5	110	70	5.5
> 4	236	126	4.5
> 3	430	194	3.5
> 2	772	342	2.5
> 1	990	218	1.5
< 1	1010	20	0.9

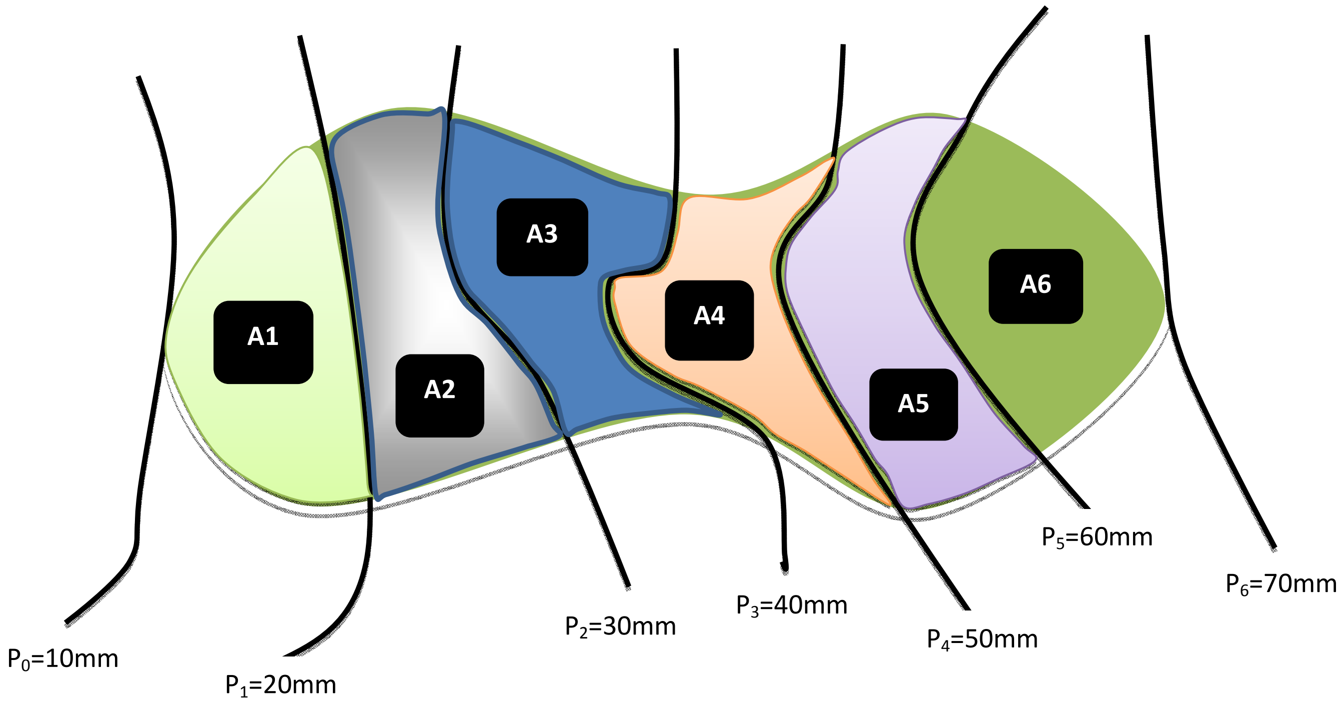
$$\boldsymbol{n_i} = \sum_{i=1}^{n} A_i \times \frac{p_{i-1} + p_i}{2} \Big/ \sum_{i=1}^{n} A_i$$

$$= \frac{40 \times 6.2 + 70 \times 5.5 + 126 \times 4.5 + 194 \times 3.5 + 342 \times 2.5 + 218 \times 1.5 + 20x0.9}{40 + 70 + 126 + 194 + 342 + 218 + 20}$$

$$= \frac{3079}{1010} = 3.05'' \cong 3''$$

Example 2.9

Use the isohyetal method to determine the average precipitation depth within the basin for the storm.



Solution

Isohyetal interval	Average Precipitation (mm)	Area (km^2)	Area x Precipitation (km^2 mm)
< 10	10	0	0
10 – 20	15	84	1 260
20 – 30	25	75	1 875
30 – 40	35	68	2 380
40 – 50	45	60	2 700
50 – 60	55	55	3 025
60 – 70	65	86	5 590
TOTAL		428	16 830

$$Average \quad Percipitation = \frac{\sum Area \times \Pr ecipitation}{\sum Area}$$

$$Average \quad Percipitation = \frac{16830}{428}$$

$$Average \quad Percipitation = 39.3 mm$$

2.4 Theoretical Exercises

1) Distinguish between the different forms of **precipitation**.

Solution

Snow: Complex ice crystals. A snowflake consists of ice crystals.
Hail: Balls of ice that are about 5 to over 125 mm in diameter. Hailstones have the potential for agricultural & other property damage.
Sleet: Results from freezing of raindrops and is usually a combination of snow and rain.
Rain: Consist of liquid water drops of a size 0.5 mm to about 7 mm in diameter.
Drizzle: Very small, numerous and uniformly dispersed water drops that appear to float while following air currents. Drizzle drops are considered to be less than 0.5 mm diameter. It is also known as warm precipitation.

2) Outline sources of error when recording readings and record-keeping by precipitation **gauge** (B.Sc., DU, 2011)

Solution

- Mistakes in reading scales of gauge,
- Displacement of some collected water during recording of reading (stick creep),
- Rainfall splash from collector,
- Loss of water needed to moisten (wetting) funnel and inside surface,
- Any change in the receiving area of precipitation, and inclination of gauge (e.g. dents in collector rim)

- Deficiency of instruments due to wind or otherwise, or the absence of regular maintenance.

3) List five natural and man-made factors that may influence the distribution of **rainfall** in a given area. (B.Sc., UAE, 1989).
4) Indicate how the following equation illustrates the method of weighting, by the ratio of the normal annual precipitation values to estimate missing records for a neighboring **monitoring station**. (B.Sc., DU, 2011)

$$P_x = \frac{\frac{N_x P_a}{N_a} + \frac{N_x P_b}{N_b} + \frac{N_x P_c}{N_c}}{3}$$

5) Define the terms used in the equation that illustrates the method of weighting to estimate **missing records** for a neighboring monitoring station (B.Sc., DU, 2012).

$$P_x = \frac{\frac{N_x P_a}{N_a} + \frac{N_x P_b}{N_b} + \frac{N_x P_c}{N_c}}{3}$$

6) What are the expected sources of error when recording **precipitation** readings in hydrological meteorological stations?
7) Explain methods of **rain** calculation? Indicate advantages and shortcomings of each method.
8) How do you assess **rainfall** data lost in a station as compared to data allocated to the neighboring stations?
9) What is the relationship between **intensity, duration and frequency of rainfall**?

2.5 Problem solving in precipitation

Arithmetic average rainfall

1) Find **average rainfall** for the rainfall data observed in the hydrological measuring stations described in the following table

Station number	Amount of rainfall, mm
1	250
2	380
3	490
4	310

2) Average rainfall in a specific region is equal to 310 mm according to the data shown in the table below for estimated rainfall in four hydrological monitoring stations: What is the **average rainfall** in station number (4) using arithmetic average method for estimating rainfall?

Station number	Amount of rain, mm
1	300
2	400
3	250
4	؟

Thiesen polygon

3) Find average precipitation in watershed according to the information and data that are described in the following table using average arithmetic method and **Thiesen polygon**. (Ans. 100.3,).

Station	Rain gauge, cm	Area, %
1	62	8
2	74	11
3	87	20
4	112	18
5	118	33
6	107	10

4) List five natural and man-made factors that may influence the distribution of rainfall in a given area. The precipitation on a catchment in Dubai of area 95 km^2 is sampled in table (1). Determine the precipitation recorded by station number (7) if the mean precipitation, as computed by **Thiessen method**, amounts to 98mm. (ans. 115.5 mm).

Rain gauge	Recorded rainfall, Feb. 1968 (mm)	Thiessen polygon on area (km^2)
1	84	4.0
2	90	4.0
3	120	10.0
4	86	5.1
5	87	15.1
6	76	30.6
7	X	6.2
8	131	20.0

5) Find precipitation by **Thiessen method** for the observed precipitation records shown in table (4) (B.Sc., DU, 2013).

$$P_{mean} = \frac{\sum_{i=1}^{n} A_i P_i}{\sum_{i=1}^{n} A_i}$$

Table: Precipitation records.

Observed precipitation, in	Area of corresponding polygon within basin boundary, sq. mile
1.59	12
2.36	112
2.84	109
3.61	122
2.46	19
3.9	84
6.11	94
5.61	68

Solution

Observed precipitation, in (1)	Area of corresponding polygon within basin boundary, sq. mile (2)	Percent total area (3)	Weighted precipitation, in Col. (1) x Col. (3)
1.59	12	1.9	0.03
2.36	112	18.1	0.43
2.84	109	17.6	0.5
3.61	122	19.7	0.71
2.46	19	3.1	0.08
3.9	84	13.5	0.53
6.11	94	15.1	0.93
5.61	68	11	0.62
	Total = 620	100	3.83

Average P = 3.83 in

Method of isohyets

6) Calculate the average rainfall of the data set in the following table using **isohyet method** rainfall.

Isohyet, cm	Area between isohyets, km^2
5	10
10	44
15	50
20	60
25	10
30	24
35	

7) Find average rainfall for the following data using **isohytal method**,

Isohyet, cm	Area between isohyets, km^2
5	15
6	25
7	95
8	105
9	55
10	25
11	

8) Find average precipitation in catchment area according to the information and data that are described in the following table using the **method of isohyets**.

Isohyets, inch	total area bounded by boundaries of the basin (ha)	Estimated average rain between isohyets, inch
6 <	40	6.5
5 <	110	5.5
4 <	236	4.5
3 <	430	3.5
2 <	772	2.5
1 <	990	1.5
1 >	1010	0.9

9) Table shows rainfall observations taken for a certain area. Estimate the mean basin precipitation. (ans. 11.06”).

Isohyets (in)	Total area enclosed within basin boundary (ha)	Estimated mean precipitation between **isohyets**
> 6	50	6.3
> 5	120	5.5
> 4	250	4.7
> 3	450	3.6
> 2	780	2.7
> 1	999	1.4
< 1	1020	0.8

10) The following rainfall observations were taken for a certain area:

Isohyets (in)	Total area enclosed within basin boundary (ha)	Estimated mean precipitation between **isohyets**
> 6	40	6.2
> 5	110	5.5
> 4	236	4.5
> 3	430	3.5
> 2	772	2.5
> 1	990	1.5
< 1	1010	0.9

Estimate the mean basin precipitation (ans. 3’).

Rainfall intensity

11) Find average rainfall intensity over an area of 6 square kilometers during a one-hour storm of frequency of once every ten years (assuming point rain of 30 mm, and inverse gamma 5.6) (Ans. 26 mm).

12) What is the average rainfall intensity over an area of 5 square kilometers during a 60 minute storm with a frequency of once in 10 years (take p = 25 mm).

13) From the precipitation data given, estimate cumulative rainfall and rainfall **intensity**.

Time (min)	0	10	20	30	40	50	60	70	80	90
Rainfall (cm)	0	0.18	0.21	0.26	0.32	0.37	0.43	0.64	1.14	3.18

Time (min)	100	110	120	130	140	150	160	170	180
Rainfall (cm)	1.65	0.81	0.52	0.26	0.42	0.36	0.28	0.19	0.17

Solution

Time (min)	Rainfall (cm)	Cumulative Rainfall (cm)	Rainfall Intensity (cm/hr)
0	0	0	
10	0.18	0.18	1.08
20	0.21	0.39	1.26
30	0.26	0.65	1.56
40	0.32	0.97	1.92
50	0.37	1.34	2.22
60	0.43	1.77	2.58
70	0.64	2.41	3.84
80	1.14	3.55	6.84
90	3.18	6.73	19.08
100	1.65	8.38	9.90
110	0.81	9.19	4.86
120	0.52	9.71	3.12
130	0.42	10.13	2.52
140	0.36	10.49	2.16
150	0.28	10.77	1.68
160	0.24	11.01	1.44
170	0.19	11.20	1.14
180	0.17	11.37	1.02

API

14) The value of the **API** for a certain station reached 42 mm in first of August, and an amount of 46 mm of rain fell on the fifth of August, also rain of 28 mm fell in the seventh of august and 34 mm on the eighth day of August. Find value of the API guide on 12th August noting that k is equal to 0.92. Calculate the amount of the index assuming no rain in the same period. Draw curve of change of index with time. (Ans. 85.3, 1.7 mm).

15) The value of the **API** for a station reached 55 mm in the first of August, an amount of 57 mm of rain fell on the sixth of August, 31 mm of rain fell in the eighth of August and 20 mm fell in the ninth day of August. Find value of API index for the 15th day of August, noting that k is equal to 0.92. Calculate the amount of index assuming no rain during the same period. Draw curve of change of index with time.

16) The antecedent precipitation index (API) is given by: $I_e = I_o k^t$, Define the parameters shown in the equation. The API for a station was 60 mm on the first of December, 64 mm rain fell on the seventh of December, 40 mm rain fell on the ninth of December, and 30 mm rain fell on the eleventh of December. Compute the API for 20th December if k = 0.85. Determine the **API** if no rain fell. (ans. 24.1, 2.7 mm).

Missing record

17) A precipitation station (X) was inoperative for some time during which a storm occurred. The storm totals at three stations (A), (B) and (C) surrounding X, were respectively 6.60, 4.80 and 3.30 cm. The normal annual precipitation amounts at stations X, A, B and C are respectively 65.6, 72.6, 51.8 and 38.2 cm. Estimate storm precipitation for station (X).
18) Rainfall data taken from the records of hydrological monitoring stations (a), (b), and (c), and (d) gave values of 17, 18, 24 and 18 mm respectively. Thiesen polygon method was chosen to calculate the average rainfall. The area of each of the polygons surrounding each station is as follows: 24, 18, 32 and 35 square kilometers for stations (a), (b), and (c), (d), respectively. Find average amount of rainfall in the region.
19) Rain record is missed from a hydraulic station (m) in a windy day. However, the estimates of rainfall at three stations (m1), (m2) and (m3) surrounding station (m) is equal to 25, 50 and 35 mm respectively. Note that the average annual precipitation at the stations (m), (m1), (m 2) and (m3) equals 500 and 700 and 590 and 440 mm, respectively. Find the value of rainfall during the storm at station (m).
20) Four hydrological monitoring stations are of similar conditions registered the data shown in the following table. Estimate missing recod.

Station	1	2	3	4
Mean annual precipitation, mm	350	1200	1100	1000
Present precipitation, mm	750	?	760	810

21) Outline sources of error when recording readings and record-keeping by precipitation gauge. Indicate how the following equation illustrates the method of weighting, by the ratio of the normal annual precipitation values to estimate missing records for a neighboring monitoring station.

$$P_x = \frac{\frac{N_x P_a}{N_a} + \frac{N_x P_b}{N_b} + \frac{N_x P_c}{N_c}}{3}$$

The records of precipitation of hydraulic monitoring stations (x) in a rainy day are missing. The data indicate that the estimates of rainfall at three stations (b), (c) and (d) adjacent to the station (x) are equal to: 70, 608 and 50 mm, respectively. If the average annual rainfall at stations (a) and (b) and (c) and (d) is: 600, 250, 510 and 120 mm, respectively, find the value of rainfall during the rain storm in station (x). (ans. 162.9 mm).

22) The average annual precipitation amounts for the gauges A, B, C and D are 1120, 935, 1200 and 978 mm. In year 1975, station D was out of operation. Station A, B, and C recorded rainfall amounts of 107, 89 and 122 mm respectively. Estimate the amount of precipitation for station D in year 1975.

Stations	Normal Annual Precipitation (mm)	Amounts of Precipitation Year 1975 (mm)
A	1120	107
B	935	89
C	1200	122
D	978	**X**

Solution

If

$N_x = 978$

Then 10% from 694 = $\frac{10}{100} \times 978 = 97.8\ mm$

Therefore, precipitation allowed = (978 – 97.8) ~ (978 + 97.8) mm

= 880.2 mm ~ 1075.8 mm

Since the average annual precipitations amounts for the gauges A and C exceeded 1075.8 mm, therefore **Normal Ratio Method** is used :-

$$P_x = \frac{978}{3}\left(\frac{107}{1120}+\frac{89}{935}+\frac{122}{1200}\right) = 95.3mm$$

23) The records of precipitation of hydraulic monitoring stations (x) in a rainy day are missing. The data indicate that the estimates of rainfall at three stations (b), (c) and (d) adjacent to the station (x) are equal to: 70, 608 and 50 mm, respectively. If the average annual rainfall at stations (a) and (b) and (c) and (d) is: 600, 250, 510 and 120 mm, respectively, find the value of rainfall during the rain storm in station (x). (B.Sc., DU, 2011)

Solution

1. Data: Pb = 70 mm, Pc = 60 mm, Pd = 50 mm, Nx = 600 mm, Nb = 250 mm, Nc = 510 mm, Nd = 120 mm.
2. Find the value of rainfall during the storm at station (a) by using the following equation: Pa = (1 ÷ 3) × {(600 × 70 ÷ 250) + (600 × 60 ÷ 510) + (600 × 50 ÷ 120)} = 162.9 mm

Chapter Three

Evaporation and transpiration

3.1 Evaporation

Evaporation is the process by which water is changed from the liquid or solid state into the gaseous state through the transfer of heat energy [15]. Evapotranspiration: the process by which water is evaporated from wet surfaces and transpired by plants [15].

Methods of estimating evaporation or transpiration include: Evaporation pans, empirical formulas, methods of water budget, methods of mass transfer and methods of energy budget [13].

Example 3.1

The daily potential evapotranspiration from a field crop at latitude 20° N in November has been predicted through use of the nomogram for the solution of Penman's equation to be equal to 2.8 mm. Estimate the mean wind speed at height of 2m, u_2, m/s. Governing conditions are as outlined in the following table (B.Sc., DU, 2013).

Table: Evaporation data.

Item	Value
Mean air temperature, T, ^oC	22
Sky cover	70 % cloud
mean humidity, h, %	60
Ratio of potential evapotranspiration to potential evaporation (E_o)	0.8

$$E_T = E_1\left(t, \frac{n}{D}\right) + E_2\left(t, \frac{n}{D}, R_A\right) + E_3\left(t, h, \frac{n}{D}\right) + E_4\left(t, u_2, h\right)$$

Where:

E_T = Evaporation from open surface of water (or equivalent in heat energy)

Δ =-Slope of vapor pressure curve at t = tan α

H = Equivalent evaporation of the total radiation on the surface of plants (the final amount - net- of energy finally remaining at a free water surface)

γ = psychrometer constant fixed device to measure humidity (= 0.66 if the temperature is measured ic centigrade and e in mbar)

E = Actual vapor pressure of air at temp t

E_a = Aerodynamic term (the term ventilation) depends on the air and low pressure steam (evaporation for the hypothetical case of equal temperatures of air and water)

t = tan α = temperature

n/D = Cloudness ratio = (actual hours of sunshine) ÷ (possible hours of sunshine)

R_A = Agot's value of solar radiation arriving at the atmosphere (assuming no clouds and a perfectly transparent atmosphere).

h = Relative humidity

u_2 = Wind speed at height of 2 m (m/s)

Solution

- Data: t = 22 °C, h = 0.6, sky Cover = 0.7, n ÷ D = 1 - sky cover Drag = 1 - 0.7 = 0.3, evaporation = 2.8 m/day, evapotranspiration = 0.8 E_o .
- From nomogram for temperature t = 22° C & the value of n/D = 0.3 then, E_1 = - 2.2 mm/day
- for Temperature t = 22 °C & tables for altitude 20° North In November, Agot's factor RA = 666 gm cal/cm^2/day & for values of n ÷ D = 0.3, E_2 = 2.6 mm/day
- For temperature t = 22 °C, n ÷ D = 0.3, h = 0.6 then: E_3 = 1.2 mm/day
- Potential evapotranspiration is given as = 2.8 mm/day
  Since evapotranspiration = 0.8*evaporation, then evaporation predicted by Pennman is:
  $0.8xE_o$ = 2.8 mm/day
  Or E_o = 3.5 mm/day
  E_o 3.5 = $E_1 + E_2 + E_3 + E_4$ = -2.2 + 2.6 + 1.2 + E_4
  This gives E_4 = 1.9 mm/day
- For a temperature t = 22 °C, E_4 = 1.9 mm/day humidity & h = 0.6, determine the wind speed at height of 2m, u_2 = 3.6 m/s then:

Example 3.2

Use the nomogram for the solution of Penman's equation to predict the daily potential evapotranspiration from a field crop at latitude 20°N in December, under the following conditions: (B.Sc., DU, 2012)

- Mean air temperature = 20^{o}C
- Mean h = 70 %
- Sky cover = 60 %cloud
- Mean u_2 = 2.5 m/s
- Ratio of potential evapotranspiration to potential evaporation = 0.8

Solution

1. Data: latitude 20°N in December, t = 20° C, h = 0.7, sky Cover = 0.6, n ÷ D = 1 - sky cover Drag = 1 - 0.6 = 0.4, u_2 = 2.5 m/s, ET = 0.8E
2. From nomogram for temperature t = 20° C and the value of n/D = 0.4 then, E_1 = - 2.4 mm/day
3. for Temperature t = 20° C and tables for altitude 20° North In December, Agot's factor R_A = 599 gm cal/cm^2/day and for values of n ÷ D = 0.4 , E_2 = 2.6 mm/day
4. For temperature t = 20° C, h = 0.7, n ÷ D = 0.4, then: E_3 = 1.4 mm/day
5. For Temperature t = 20° C, speed u_2 = 2.5 m/s and humidity h = 0.7, then: E_4 = 1.1 mm/day
6. Find E_o from the equation:
   $E_o = E_1 + E_2 + E_3 + E_4$ = - 2.4 + 2.6 + 1.4 + 1.1 = 2.7 mm/day
   Evapotranspiration = 0.7 E_o = 0.8 x 2.7 = 2.16 mm/day.

Example 3.3

Use the nomogram for the solution of Penman's equation to predict the daily potential evapotranspiration from a field crop at latitude 20°N in November, under the following conditions: (B.Sc., DU, 2012)

- Mean air temperature = 20^{o}C
- Mean h = 80 %

- Sky cover = 70 %cloud
- Mean u_2 = 2.5 m/s
- Ratio of potential evapotranspiration to potential evaporation = 0.7

Solution

1) Data: sky Cover = 0.7, n ÷ D = 1 - sky cover Drag = 1 - 0.7 = 0.3, t = 20□C, h = 0.8, u_2 = 2.5 m/s, h = 0.8, Ratio of evapotranspiration to evaporation = 0.7.
2) From nomogram for temperature t = 20□C and the value of n/D = 0.3 then, E_1 = -2.1 mm/day
3) For altitude 20□ North In November, from table find Agot's factor R_A = 666 gm cal/ cm^2/day. Then, for Temperature t = 20□C and for values of n ÷ D = 0.3 and for R_A = 666 the value of E_2 = 2.3 mm/day
4) For temperature t = 20□C, h = 0.8 and n ÷ D = 0.3, then: E_3 = 1.2 mm/day
5) For Temperature t = 20□C, and the speed u_2 = 2.5 m / s and humidity h = 0.8, then: E_4 = 0.55 mm/day
6) Find E_o from the equation:
   $E_o = E_1 + E_2 + E_3 + E_4 = -2.1 + 2.3 + 1.2 + 0.55 = 1.85$ mm/day
   Evapotranspiration = 0.7 Eo = 0.7 x 1.85 = 1.295 mm/day.

3.2 Theoretical Exercises

10) Outline importance of the evaporation process (B.Sc., DU, 2012).

Solution

- Affects study of water resources due to its impact on yield of river basin,
- Affects the necessary capacity of reservoirs,
- Determines size of pumping plant,
- Affects water consumptive use of water by crops ,
- Affects yield of groundwater supplies

11) Penman equation of evaporation from free water surfaces is based on two requirements that need to be met for continuous evaporation to occur: there must be a supply of energy to provide latent heat of vaporization, and there must be some mechanism for removing the vapor, once produced. Define the parameters shown in the equation (B.Sc., DU, 2012)

$$E_T = E_1\left(t, \frac{n}{D}\right) + E_2\left(t, R_A, \frac{n}{D}\right) + E_3\left(t, \frac{n}{D}, h\right) + E_4\left(t, u_2, h\right)$$

12) What the main differences between evaporation and transpiration?
13) What are Penman's assumptions to estimate amount of evaporation?
14) Explain the different factors affecting the evaporation Process.

   a- Sun Radiation

   Process of conversion from water into vapor continue if the energy is there (sun light as the heat energy), and cloud will be the barrier of evaporation.

   b- Wind

   If water evaporates to the atmosphere, the level between land surface and air will be saturated by vapor, then the process of evaporation stops. In order for the process to continue, the saturation level must be changed with dry air. This changing is possible if there is wind which blows the component of vapor.

c- Relative Humidity

If the relative humidity is up, so then the potential of air to absorb water is lower so then the evaporation is lower as well.

d- Temperature

If the temperature of air and soil is high, therefore the process of evaporation will be faster.

3.3 Problem solving in evaporation

1) Use Penman nomogram to solve its equation to predict daily evapotranspiration expected from field plants at latitude 40 degrees north in April under the following conditions: intermediate air temperature 20 degrees Celsius, average humidity 70%, coverage of sky 60% clouds, relative speed at a height of two meters 2.5 m/s, and expected rate of transpiration to expected evaporation 0.7. What is the difference in the result at latitude of 40 degrees south? (Ans. 2.5 mm/day).
2) Use the Penman nomogram to solve its equation to predict expected daily evapotranspiration from field plants at latitude 60 degrees north in March and June, for an expected rate of evapotranspiration 65 percent of the expected evaporation, under the following conditions:

	March	June
Intermediate air temperature (° C)	5.5	15
Medium relative humidity (%)	79	77
Sky coverage (% clouds)	45	55
Relative velocity of wind (m/s)	2.5	3

3) Use the nomogram for the solution of Penman's equation to predict the daily potential evapotranspiration from a field crop at latitude 20°N in July, under the following conditions:
   Mean air temperature = 20°C
   Mean h = 80 %
   Sky cover = 70 %cloud
   Mean u2 = 2.5 m/s
   Ratio of potential evapotranspiration to potential evaporation = 0.8
4) Find amount of water evaporating from the surface of a lake during the month of March if the median value of the maximum temperature of the water surface of the lake during this period is 18 degrees Celsius, the temperature of dry air at a height of 2 meters above the lake surface is 20 degrees Celsius, humidity tw = 17 degree C, and the mean wind speed is 1.5 m/s at the same height noting that the lake did not freeze during the monitoring period.
5) Use the nomogram for the solution of Penman's equation to predict the daily potential evapotranspiration from a field crop at latitude 20°N in November, under the following conditions:
   - Mean air temperature = 20^{o}C
   - Mean h = 80 %
   - Sky cover = 70 %cloud
   - Mean u_2 = 2.5 m/s
   - Ratio of potential evapotranspiration to potential evaporation = 0.7

   (Ans. 1.295 mm/day).

Chapter Four

Infiltration and percolation

4.1) Infiltration

Infiltration is the movement of water through the soil surface into the soil. Percolation is the movement of water through the soil.

Factors affecting infiltration include: surface entry, transmission through soil, depletion of available storage capacity in soil and ccharacteristics of permeable medium.

Important indicators used to estimate infiltration (as an average rate throughout the period of storm and rain): Average infiltration method, ϕ-index, W-index and ratio to surface flow method.

Φ - index is that rate of rainfall above which the rainfall volume equals the runoff volume. The index reflects the average infiltration rate, and is found from a time-rainfall intensity curve.

Example 4.1

a) For a total rainfall distributed as shown in the table (1), the φ-index of the catchment area for a certain surface runoff is found to be 9 mm/hr (B.Sc., DU, 2012).

Table (1) Rainfall intensity versus time.

Determine:

Time	Rainfall intensity (mm/hr)
0	0
1	5
2	15
3	20
4	20
5	14
6	1

i. The value of surface runoff producing a ϕ–index of 9 mm/hr.
ii. The total rainfall in the catchment area.

b) If the same rainfall had been distributed as shown in table (2), compute the value of ϕ–index that would yield the same surface runoff. Comment on your answers.

Table (2) Rainfall intensity versus time.

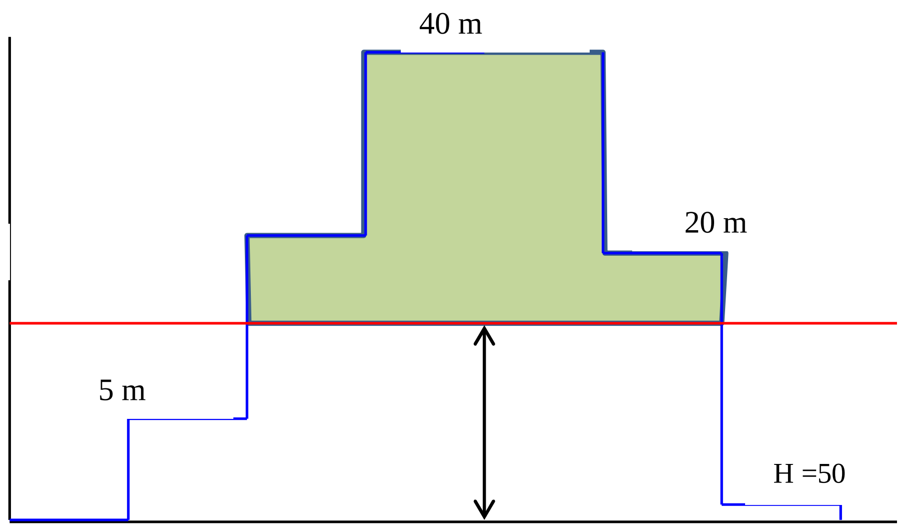
Time	Rainfall intensity (mm/hr)
0	0
1	9
2	16
3	27
4	10
5	8
6	5

Solution

a) ϕ-index is the average rainfall intensity above which the volume of rainfall equals the volume of runoff.

b) Surface runoff = shaded area = (15-9)*1 + (20-9)*1 + (20-9)*1 + (14-9)*1 = 6*1 + 11* 1 + 11* 1 + 5*1 = 33 mm

Total rainfall = 5*1 + 15* 1 +20*1 + 20*1 + 14* 1 + 1* 1 = 75 mm



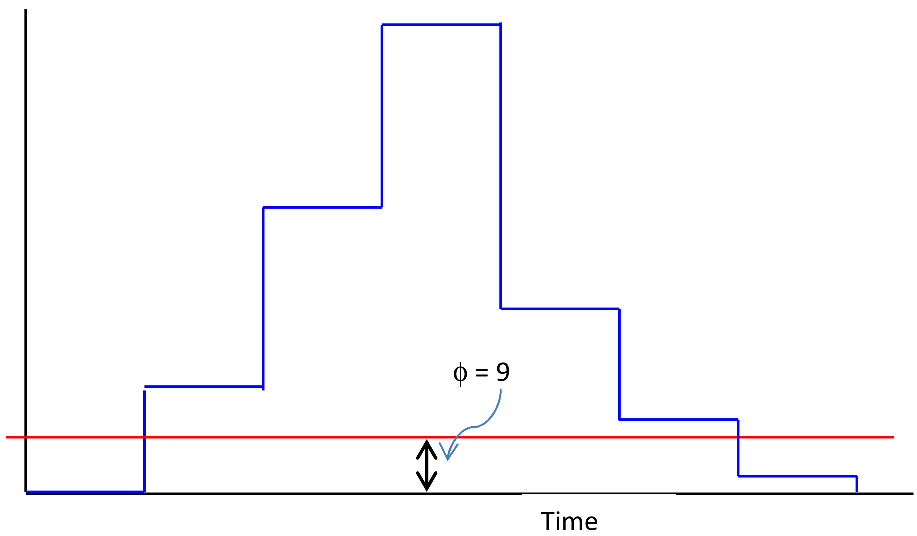
c)

Rate of rainfall above φ runoff volume

$\therefore$ (9 - φ)×1 + (16 - φ)×1 + (27 - φ)×1 + (10 - φ)×1 + (8 - φ)×1 = 33 mm

$\therefore$ 70 - 5φ = 33

$\therefore$ φ = 7.4 mm/hr



c) The results show that one determination of the f-index is of limited value and that many such determinations should be made, and averaged, before the index is used.

Example 4.2

For a total rainfall of 44 mm, distributed as shown in the table (3), establish the φ index of the catchment area for a surface runoff of 19.5 mm. (B.Sc., DU, 2012)

Table (3) Rainfall intensity versus time.

Time	Rainfall intensity (mm/hr)
0	0
1	4
2	21
3	9
4	6
5	4

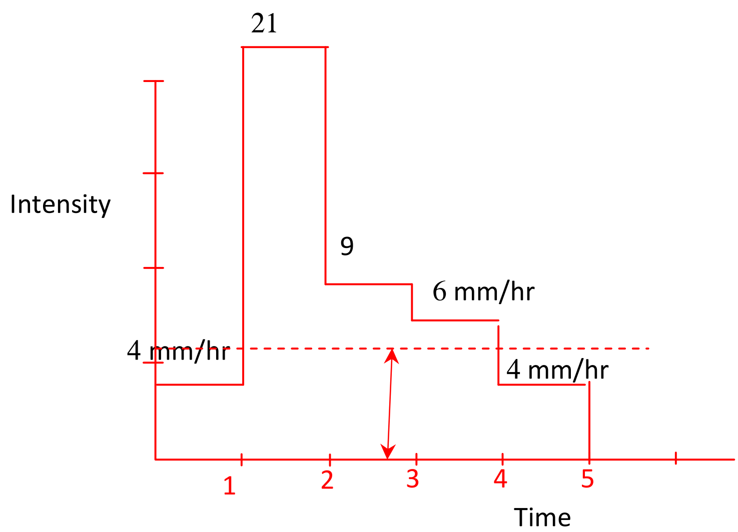
Solution

Rate of rainfall above φ runoff volume

$\therefore (21 - \varphi)\times 1 + (9 - \varphi)\times 1 + (6 - \varphi)\times 1 = 19.5$ mm

$\therefore 36 - 3\varphi = 19.5$

$\therefore \varphi = 5.5$ mm/hr



Example 4.3

A storm with 10.0 cm precipitation produced a direct runoff of 5.8 cm. Given the time distribution of the storm as below, estimate the ϕ-index of the storm.

Time from start (hr)	1	2	3	4	5	6	7	8
Incremental rainfall in each hour (cm)	0.4	0.9	1.5	2.3	1.8	1.6	1.0	0.5

Solution

Total Infiltration = 10.0 cm - 5.8 cm = 4.2 cm

Assume time of rainfall excess, t_e = 8 hr (for the first trial)

Then,

$$Index, \phi \quad = \quad \frac{10.0 - 5.8}{8} \quad = \quad 0.525\, cm/hr$$

But this value of ϕ makes the rainfalls of the first hour and eight hour ineffective as their magnitude is less than 0.525 cm/hr.

The value of t_e is therefore modified.

Assume time of rainfall excess, te = 6 hr (for the second trial)

In this period, Infiltration = 10.0 - 0.4 - 0.5 - 5.8 = 3.3 cm

$$Index, \phi \quad = \quad \frac{3.3}{6} \quad = \quad 0.55\, cm/hr$$

This value of ϕ is satisfactory as it gives,

t_e = 6 hr, and by calculating rainfall excesses.

Time from start (h)	1	2	3	4	5	6	7	8
Rainfall Excess (cm)	0	0.35	0.95	1.75	1.25	1.05	0.45	0

Total Rainfall excess = 5.8 cm = total runoff

Example 4.4

Following data was obtained from a catchment of an area of 300 km^2.

Time from start (h)	1	2	3	4	5	6	7	8
Incremental rainfall in each hour (cm)	0.5	1.1	1.3	2.1	2.0	1.8	1.0	0.4

Solution

Estimate the ϕ index of the storm if the volume of surface runoff was 16.5 x 10^6 m^3.

Total Precipitation, P

= 0.5+1.1+1.3+2.1+2.0+1.8+1.0+0.4

= 10.2 cm

Runoff, R

= (16.5 x 10^6 m^3) / (300 x 10^6 m^2)

= 0.055 m = 5.5 cm

Total Infiltration, I = P - R

Assume time of rainfall excess, te = 8 hr

(for the first trial)

Then,

$$Index, \phi \quad = \quad \frac{P - R}{t_e} \quad = \quad (10.2 - 5.5) / 8 = 0.5875 \text{ cm / hr}$$

But this value of ϕ makes the rainfalls of the first hour and eight hour ineffective as their magnitude is less than 0.5875 cm/hr.

- The value of te is therefore modified.

- Assume time of rainfall excess, te = 6 hr
  (for the second trial)

In this period, Infiltration =

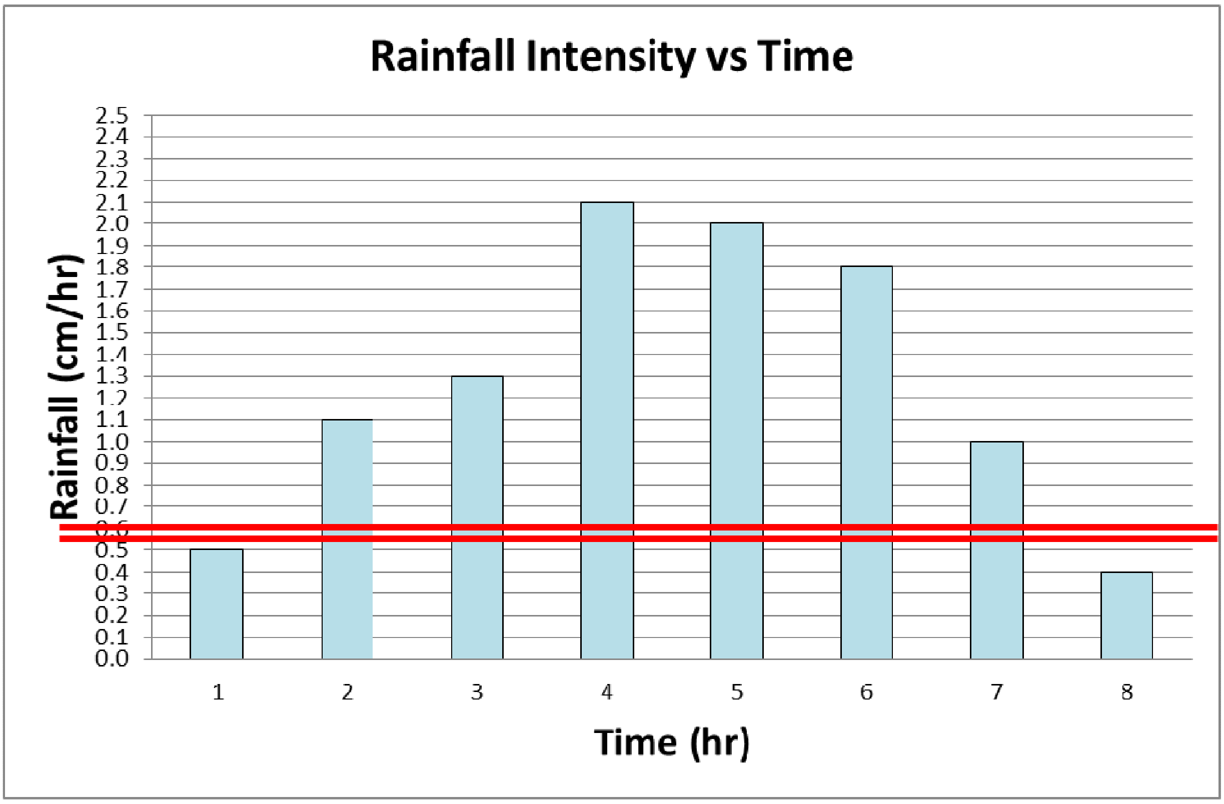
In this period, Infiltration =

$$Index, \phi \quad = \quad \frac{P - R}{t_e} \quad =$$

This value of ϕ is satisfactory as it gives,
te = 6 hr, and by calculating rainfall excesses.

Time from start (h)	1	2	3	4	5	6	7	8
Rainfall Excess (cm)	0	0.47	0.67	1.47	1.37	1.17	0.37	0

Total Rainfall excess = 5.5 cm = total runoff



4.2 Antecedent precipitation index, API

Example 4.5

The API for a station was 39 mm on first December, 61 mm rain fell on fifth December, 42 mm on 7 December & 19 mm on 8 December. Compute the anticedent precipitation index for 12 December, if k = 0.89, and for same data assuming no rain fell (B.Sc., DU, 2013).

$$I_t = I_o * k^t$$

Where:

I_t = Index value at t days later (mm)

I_o = Initial value to the index (mm)

k = A recession constant, of magnitude between 0.85 to 0.98 (usually taken for a value of about 0.92).

t = Time (day).

Solution

- Data: amount of precipitation in different days of the month of December.
- Since $I_t = I_o k^t$ & assuming t = 1 produces: It = $I_o k$. Which means that: the index for any day is equal to that value in the previous day multiplied by the coefficient k. then if rain fell in the day, the amount of rain is added to the index.
- For the given data index can be estimated as follows: On the first day of December, I_1 = 39 mm Just on the fifth day of December $I_5 = 39*(0.89)^4$, I_5 = 24.5 mm
- On the fifth day of December rain should be added: I_5 = 24.5+ 61= 85.5mm
- Just on the seventh day of December $I_7 = 85.5* (0.89)^2$, I_7 = 67.7 mm
- On the seventh day of December rain should be added : I_7 = 67.7 + 42 = 109.7mm
- Just on the eighth day of December $I_8 = 109.7*(0.89)^1$, I_8 = 97.6 mm
- On the eighth day of December rain should be added: I_8 = 97.6 + 19= 116.6 mm
- In the twelfth day of December a $I_{12} = 116.6*(0.89)^4$, I_{12} = 73.2 mm (with rain in different days)
- In the case of lack of rain, the value is equal to the directory: $I_{12} = 39*(0.89)^{11}$, I_{12} = 10.8 mm (with no rain)

4.3) Theoretical Exercises

1) The antecedent precipitation index (API) is given by: $I_e = I_o k^t$, Define the parameters shown in the equation (B.Sc., UAE, 1989, B.Sc., DU, 2012).

   Solution

   I_t = index value at t days later

   I_o = initial value of index

   k = a recession constant.

2) Define ϕ-index. (B.Sc., DU, 2012)
3) Illustrate major factors that may affect infiltration of water within a certain catchment area. (B.Sc., UAE, 1989).
4) What are the factors affecting infiltration of water into the soil. How is it measured?
5) What is the difference between infiltration and percolation? Indicate how both are measured.
6) Elaborate on indicators used to estimate infiltration. Which one is the best to be used? Why?

4.4) Problem solving in infiltration

ϕ-index

1) Find value of ϕ-index in a catchment area to make a surface runoff of 19.5 mm, knowing that the total value of the rain for an area equal to 44 mm as indicated in the following table: (Ans. 5.5 mm/hr).

Time, hr	Rainfall intensity, mm/hr
0	0
1	4
2	21
3	9
4	6
5	4

2) For a total rainfall of 150mm, distributed as shown in table (2), establish the φ index of the catchment area for a surface runoff of 72mm. (B.Sc., UAE, 1989).

Time	Rainfall intensity (mm/hr)
0	0
1	16
2	29
3	35
4	16
5	8
6	19
7	27

Compute the change in φ index for the same catchment in (b) above if a second storm gave rise to a runoff equivalent to 68mm while the hourly rainfall of the storm indicated the following distribution: (B.Sc., UAE, 1989). (ans. 11.7 mm/hr,).

Time	Rainfall intensity (mm/hr)
0	0
1	15
2	43
3	61
4	24
5	12

3) Determine the φ index for the catchment area as affected by the two storms indicated in (a) and (b) above. (B.Sc., UAE, 1989).

Solution

b) Rate of rainfall above φ runoff volume

$\therefore (16 - \varphi)\times1 + (29 - \varphi)\times1 + (35 - \varphi)\times1 + (16 - \varphi)\times1 + (19 - \varphi)\times1 + (27 - \varphi)\times1$

$\therefore 142 - 6\varphi = 72$

$\therefore \varphi = \frac{70}{6} = 11.7\ mm/hr$

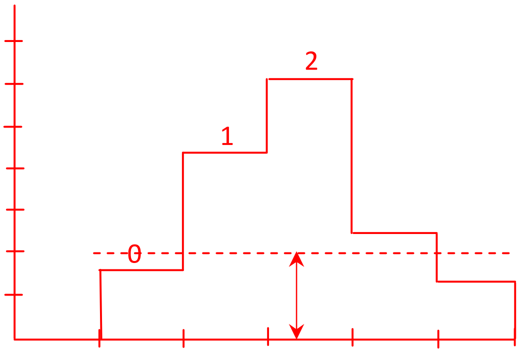
a) $(43 - \varphi_2)\times1 + (61 - \varphi_2)\times1 + (24 - \varphi_2)\times1 = 68$

$128 - 3\varphi_2 = 68$

$60 = 3\varphi_2 \quad \varphi_2 = 20$mm/hr

$$\therefore Change\ in\ \varphi_2 = \frac{\varphi - \varphi_2}{\varphi} = \frac{11.7 - 20}{11.7} \times 100 = -71\%$$

i.e. φ increased by 71%



API

4) The API for a station was 60 mm on the first of December, 64 mm rain fell on the seventh of December, 40 mm rain fell on the ninth of December, and 30 mm rain fell on the eleventh of December. Compute the API for 20th December if k = 0.85. Determine the API if no rain fell (B.Sc., DU, 2012) .

Solution

Since $I_t = I_o k^t$, letting t = 1, $k_i = kI_o$, $I_o = 60$ mm
Just on 7th, index $I_6 == 60x(0.85)^6 = 22.6$ mm
After rainfall $I_7 = 22.6 + 64 = 86.6$ mm
Just on 9th, index $= 86.6x(0.85)^2 = 62.6$ mm
After rainfall $I_9 = 62.6 + 40 = 102.6$ mm
Just on 11th, index $= 102.x(0.85)^2 = 74.1$ mm
After rainfall $I_{11} = 74.1 + 30 = 104.1$ mm
On 20th day, $I_{20} = 104.1x(0.85)^9 = 24.1$ mm
If no rain fell
$I_{20} = 60x(0.85)^{19} = 2.7$ mm

5) The API for a station was 55mm on the first of August, 57mm rain fell 0n the sixth of August, 31mm rain fell on the eighth of August, and 20mm rain fell on the 9th August. Compute the API for 15th August if k = 0.92. Determine the APU if no rain fell. (B.Sc., UAE, 1989).

Solution

I_t = index value at t days later
I_o = initial value of index
k = a recession constant.
Since $I_t = I_o k^t$, letting t = 1, $k_i = kI_o$, $I_o = 55$mm
Just on 6th, index $I_6 == 55x(0.92)^5 = 36.3$ mm
After rainfall $I_6 = 36.3 + 57 = 93.3$ mm
Just on 8th, index $= 93.3x(0.92)^2 = 79$ mm
After rainfall $I_8 = 79 + 31 = 110$mm
Just on 9th, index $= 110x(0.92)^1 = 101.2$ mm
After rainfall $I_9 = 101.2 + 20 = 121.2$ mm

On 15th day, $I_{15} = 121.2x(0.92)^6$ 73.5 mm
If no rain fell
$I_{15} = 55x(0.92)^{14} = 17.1$ mm

6) The value of API for rainfall monitoring stations reached 42 mm in the first day of October, and an amount of 46 mm of rain fell in the fifth day of October, and an another amount of rain of 28 mm fell on the seventh day and 34 mm fell on the eighth day of October. Find the value of the API on 12 October assuming that k is equal to 0.92. Calculate the amount of index assuming no rain fell in the same period.
7) The API for a station was 55mm on the first of August, 57mm rain fell 0n the sixth of August, 31mm rain fell on the eighth of August, and 20mm rain fell on the 9th August. Compute the API for 15th August if k = 0.92. Determine the API if no rain fell. (ans. 17.1 mm).
8) The value of the API for a certain station reached 42 mm in first of August, and an amount of 46 mm of rain fell on the fifth of August, also rain of 28 mm fell in the seventh of august and 34 mm on the eighth day of August. Find value of the API guide on 12th August noting that k is equal to 0.92. Calculate the amount of the index assuming no rain in the same period. Draw curve of change of index with time. (Ans. 85.3, 1.7 mm).
9) The value of the API for a station reached 55 mm in the first of August, an amount of 57 mm of rain fell on the sixth of August, 31 mm of rain fell in the eighth of August and 20 mm fell in the ninth day of August. Find value of API index for the 15th day of August, noting that k is equal to 0.92. Calculate the amount of index assuming no rain during the same period. Draw curve of change of index with time.
10) The antecedent precipitation index (API) is given by: Ie = Iokt, Define the parameters shown in the equation. The API for a station was 60 mm on the first of December, 64 mm rain fell on the seventh of December, 40 mm rain fell on the ninth of December, and 30 mm rain fell on the eleventh of December. Compute the API for 20th December if k = 0.85. Determine the API if no rain fell. (ans. 24.1, 2.7 mm).

Chapter Five

Groundwater Flow

5.1 Groundwater

Groundwater represents that part of reserved water in a porous aquifer, resulting from infiltration of rainfall through the soil and its penetration to the underlying strata.

Example 5.1

Outline most important factors affecting productivity of a well (B.Sc., DU, 2013).

Solution

Most important factors affecting productivity of a well:

- Lowering of groundwater within aquifer (drawdown aspects).
- Dimensions of aquifer & its lateral extent.
- Ground water storage.
- Transmissivity & specific yield or storage coefficient of aquifer.
- Conditions of flow (steady or unsteady).
- Depth of well.
- Establishment of well & methods of construction, properties & condition.

Table (5.1) Expected well yield.

Well diameter, cm	Expected well yield, m^3/d
15	< 500
20	400 to 1000
25	800 to 2000
30	2000 to 3500
35	3000 to 5000
40	4500 to 7000
50	6500 to 10000
60	8500 to 17000

Example 5.1

A well is 30 cm diameter and penetrates 50 m below the static water table. After 36 hr of pumping at 4.0 m^3/minute the water level on a test well 200 m distance is lowered by 1.2m and in a well 40 m away the drawdown is 2.7 m (B.Sc., DU, 2013).

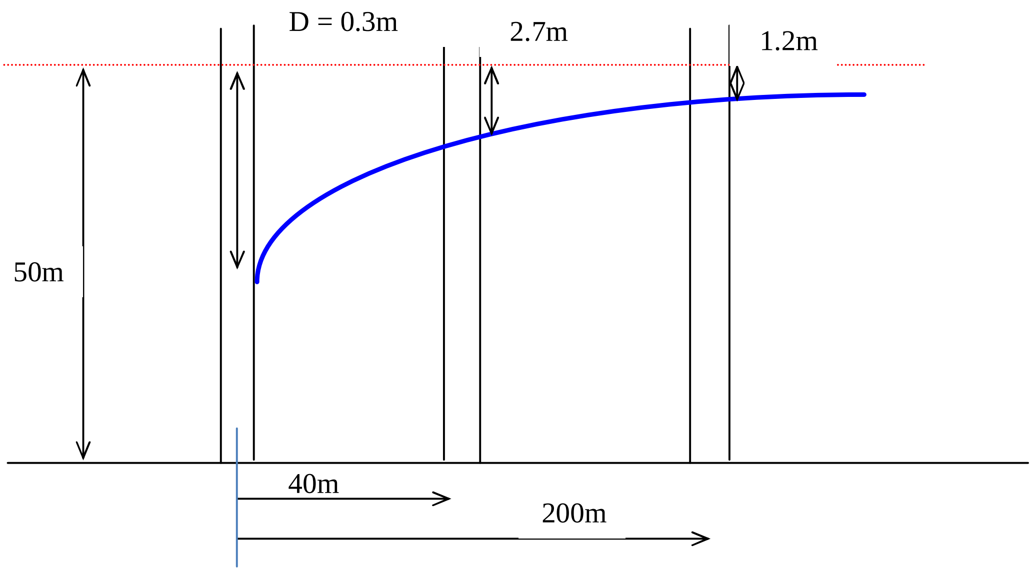
i) Determine radius of zero draw-down.
ii) Find coefficient of permeability.
iii) Compute draw-down in the pumped well.
iv) What is the transmissibility of the aquifer?

Using expected well yield estimates as presented in table (5.1), comment about yield of the well as related to its diameter, & suggest a more suitable well diameter. Explain and validate your answer (B.Sc., DU, 2013).

$$Q = \frac{\pi k \left(H^2 - h^2\right)}{Ln \frac{R}{r}}$$

Solution

- Given: D = 0.3 m, H = 50 m, r_1 = 40 m, x_1 = 2.7 m, r_2= 200 m, x_2= 1.2 m, Q_o = 4000 L/min.



Find $h_1 = h - x_1 = 50 – 1.2 = 47.3$ m, and $h_2 = h - x_2 = 50 – 2.7 = 48.8$ m.
Use the following equation for both observation wells:

$$Q = \frac{\pi k\left(H^2 - h^2\right)}{Ln \frac{R}{r}}$$

Where:
Q = Flow through well at a distance r.
h = Depth below original water level.
R = radius of zero draw down.
k = coefficient of permeability.
H = depth of aquifer.

$$\therefore \left[\frac{\pi k\left(H^2 - h^2\right)}{Ln \frac{R}{r}}\right]_{\text{ist well}} = \left[\frac{\pi k\left(H^2 - h^2\right)}{Ln \frac{R}{r}}\right]_{\text{2nd well}}$$

By substituting given values into the previous equation, then:

$$\therefore \left[\frac{\left(50^2 - 47.3^2\right)}{Ln \frac{R}{40}}\right]_{\text{ist well}} = \left[\frac{\left(50^2 - 48.8^2\right)}{Ln \frac{R}{200}}\right]_{\text{2nd well}}$$

- This yields R = 751.5 m.
- Find the permeability coefficient by using the data of one of the wells.

Thus, for h = 50 m, ho = 47.3 m, r = 40 m, R = 751.5 m, Q = $4000*10^{-3}*60*24$ = 5760 m^3/day,

$$k = \frac{QLn\frac{R}{r_1}}{\pi\left(H^2 - h_1^2\right)} = \frac{5760Ln\frac{751.5}{40}}{\pi\left(50^2 - 47.3_1^2\right)} = 20.5 \quad m/d$$

- Depth of the water in the pumped well may be found as:

$$Q_o = \frac{\pi k\left(H^2 - h_o^2\right)}{Ln\frac{R}{r_o}} \qquad \text{Or} \qquad h_0^2 = H^2 - \frac{Q}{\pi k}Ln\frac{R}{r_o} = 50^2 - \frac{5760}{\pi x20.5}Ln\frac{751.5}{0.15}$$

  This yields, h = 41.7 m
  Determine the draw-down at the well as:
  $r_o = h - h_1 = 50 - 41.7 = 8.3$ m.

- From table for a well diameter of 30 cm, yield is 2000 – 3500 m^3/d.
  The amount of water abstracted is Q_o = 4000 L/min = 4000*60*24/1000 = 5760 m^3/d. A better design would be selected a well of diameter of 40 cm (giving a yield of 5867 m^3/d for computed drawdown sat well (O.k. between 4500 - 7000).

$$Q_o = \frac{\pi \times 20.5\left(50^2 - 41.7^2\right)}{Ln\frac{751.5}{(0.4/2)}} = 5867 \quad \text{cubic meter per day}$$

Example 5.2

A fully-penetrating well, with an outside diameter of 50 cm, discharges a constant 3 m^3/min from an aquifer whose coefficient of transmissibility is 0.03 m^2/s. The aquifer is in contact with a lake 2 km away & has no other source of supply (B.Sc., DU, 2012).

i. Estimate the drawdown at the well surface. (Take R_0 as twice distance between aquifer & lake).
ii. Using expected well yield estimates as presented in table (1), comment about yield of the well as related to its diameter, & suggest a more suitable well diameter. Explain your answer.
iii. Give a suggestion for type of aquifer soil with assuming an aquifer thickness of 20 m.

Solution

a) Data: $Q_0 = 3$ m^3/min = 3*60*24 = 5760 m^3/day, R_o = 2xL = 2x2000 = 4000m, D = 0.5 m, r_o = 0.5/2 = 0.25 m, T = 0.03 m^3/s = 1.8 m^2/min
b) Using equation
c)

$$S_o = \frac{Q_o}{2\pi kH}\ln\frac{R_o}{r} = \frac{Q_o}{2\pi T}\ln\frac{R_o}{r} \qquad S_o = \frac{3}{2\pi \times 1.8}\ln\frac{4000}{0.25}$$

Hence, drawdown at well face is 2.57 m

- From table of well yield this diameter (= 0.5m) gives a yield in range of 6500 – 10000 m^3/d. Nonetheless, needed constant flow ought to be 4320 m^3/d. This suggests using a well of diameter of 35 cm to have a yield between 3000 to 5000 m^3/d, thus satisfying need.

- The actual well yield according to aquifer properties and computed drawdown for a well diameter of 35 cm would then be:

$$Q_o = \frac{2\pi T}{Ln\frac{R}{r_o}} S_o == \frac{2\pi \times 1.8 * 60 * 24 * 2.57}{Ln\frac{3000}{0.175}} = 4167 \;\; m^3/d \quad between\ 3000\ and\ 5000\ \ O.K.$$

- Determine permeability k = T/H = (1.8*60*24)/20 = 129.6 m/d
- From figure of range of permeability in natural soils, this value of k suggests **fine gravel** soil description.

Example 5.3

A fully-penetrating well, with an outside diameter of 0.3 m, discharges a constant 4 m^3/min from an aquifer whose coefficient of transmissibility is 1.4 m^2/min. The aquifer is in contact with a lake 1.5 km away & has no other source of supply(B.Sc., DU, 2012).

i. Estimate the drawdown at the well surface. (Take R_0 as twice distance between aquifer & lake).
ii. Using expected well yield estimates as presented in table (1), comment about yield of the well as related to its diameter, & suggest a more suitable well diameter. Explain your answer.
iii. Give a suggestion for type of aquifer soil with assuming an aquifer thickness of 25 m.

Solution

d) Theim's equation assumptions
- Aquifer homogeneous, isotropic & extended to infinity.
- Well penetrates thickness of aquifer carrying water & diverting water from it.
- Transmissivility (hydraulic conductivity) is constant in each place & does not depend on time.
- Pumping is conducted at a steady rate for a period so that it may assume a stable condition.
- Stream lines are radial (horizontal).
- Flow is laminar.

e) Data: Q_0 = 4 m^3/min = 4*60*24 = 5760 m^3/day, R_o = 2xL = 2x1500 = 3000m, D = 0.3 m, r_o = 0.3/2 = 0.15 m, T = 1.4 m^2/min

f) Using equation

g)

$$S_o = \frac{Q_o}{2\pi kH}\ln\frac{R_o}{r} = \frac{Q_o}{2\pi T}\ln\frac{R_o}{r} \qquad S_o = \frac{4}{2\pi \times 1.4}\ln\frac{3000}{0.15}$$

Hence, drawdown at well face is 4.5 m

-
- From table of well yield this dia (= 0.3m) gives a yield in range of 2000 – 3500 m^3/d. Nonetheless, needed constant flow ought to be 5760 m^3/d. This suggests using a well of diameter of 40 cm to have a yield between 4500 to 7000 m^3/d, thus satisfying need.
- The actual well yield according to aquifer properties and computed drawdown for a well diameter of 40 cm would then be:

$$Q_o = \frac{2\pi T}{Ln\frac{R}{r_o}} S_o == \frac{2\pi \times 1.4 * 60 * 24 * 4.5}{Ln\frac{3000}{0.2}} = 5929 \;\; m^3/d > 5760\ O.K.$$

- Determine permeability k = T/H = (1.4*60*24)/25 = 80.6 m/d
- From figure of range of permeability in natural soils, this value of k suggests **coarse sand** soil description.

Example 5.4

The static level of water table in an unconfined aquifer was 30 m above the underlying impermeable stratum. A 150 mm diameter well, penetrating the aquifer to its full depth, was pumped at the rate of 20 litres per second. After several weeks of pumping, the drawdown in observation wells 20 m and 50 m from the well were 3.5 m and 2 m respectively, and the observed drawdowns were increasing very slowly (B.Sc., DU, 2012).

a) Assuming equilibrium conditions, estimate the hydraulic conductivity and transmissivity of the aquifer.
b) Estimate the drawdown just outside the pumped well.
c) What will be the yield of a 300 mm diameter well which will produce the same drawdowns just outside the well and at the 50 m distance observation well in (2)? What would be the drawdown at a nearer observation well?

Solution

Determine Q = $20 \times 10^{-3} \times 60 \times 60 \times 24 = 1728\ m^3/d$

$$Q = \frac{\pi k (H^2 - h^2)}{ln\frac{R}{r}}$$

$$\left.\frac{\pi k (H^2 - h^2)}{ln\frac{R}{r}}\right]_{1st\ well} = \left.\frac{\pi k (H^2 - h^2)}{ln\frac{R}{r}}\right]_{2nd\ well}$$

$$\frac{30^2 - (30 - 3.5)^2}{ln\frac{R}{20}} = \frac{30^2 - (30 - 2)^2}{ln\frac{R}{50}}$$

∴ R = 183.5 m

$k = \frac{Q.ln\frac{R}{r}}{\pi(H^2 - h^2)} = \frac{1728 ln\frac{183.5}{20}}{\pi[30^2 - (30-3.5)^2]}$ = 6.16 m/d = 7.13×10^{-5} m/s

T = kH = 6.16×30 = 184.9 m^2/d

b) Depth of water in well, $h^2 = H^2 - \frac{Q}{\pi k} ln\frac{R}{r} = 30^2 - \frac{1728}{\pi \times 6.16} ln\frac{183.5}{0.075}$ = 203.8

H = 14.3 m

Drawdown just outside the = 30 – 14.3 = 15.7 m.

c) Yield

$$Q = \frac{\pi k (H^2 - h^2)}{ln\frac{R}{r}} = \frac{\pi \times 6.16[30^2 - (30-2)^2]}{ln\frac{183.5}{0.15}} = 315.8\frac{m3}{d} = 3.66 \times 10^{-3}\, m^3/s$$

$$h^2 = 30^2 - \frac{315.8}{\pi \times 6.16} ln\frac{183.5}{0.15} = 784$$

h = 28 m.

Drawdown at a nearer observation well = 30 – 28 = 2 m

Example 5.5

A well of diameter 30 cm penetrates an aquifer, water depth in it 15 meters before pumping. When pumping is being done at a rate of 3000 liters per minute, the drawdowns in two observation wells 40 and 90 meters away from the well are found to be 1.3 and 0.7 meters, respectively (B.Sc., DU, 2011).

i. Find radius of zero draw down.
ii. Determine the coefficient of permeability, and
iii. Compute drawdown in the well.
iv. Give a suggestion for type of aquifer soil for the estimated permeability.
v. Comment on yield of well compared to its diameter. Give suggestions for improvement?

Solution

1) Data: Data on wells.
2) Use following equation for each well

   r = 40 m, s = 1.3 m, h = 15 – 1.3 = 13.7 m

   r = 90 m, s= 0.7m, h = 15 – 0.7 = 14.3 m

$$Q_o = \frac{\pi k\left(H^2 - h_0^2\right)}{Ln\frac{R}{r_o}}$$

$$\therefore \left[\frac{\pi k\left(H^2 - h_0^2\right)}{Ln\frac{R}{r_o}}\right]_{ist\,well} = \left[\frac{\pi k\left(H^2 - h_0^2\right)}{Ln\frac{R}{r_o}}\right]_{2nd\,well} \qquad \left[\frac{\left(15^2 - 13.7^2\right)}{Ln\frac{R}{40}}\right]_1 = \left[\frac{\left(15^2 - 14.3^2\right)}{Ln\frac{R}{90}}\right]_2$$

i) Then: R can be found = 242.2 m

ii) Find coefficient permeability from the equation to the data of the well about 40 m away: H = 15 m, s = 1.3 m, h = 15 - 1.3 = 13.7 m, R = 254.9 m, Q = 3000 L/min = 3 m^3/min = 3*60*24 = 4320 m^3/day

$$k = \frac{Q Ln\frac{R}{r_o}}{\pi\ H^2\quad h_0^2} = \frac{4320 Ln\frac{242.29}{40}}{\pi\ 15^2\quad 13.7^2} = 66.36 m/d$$

iii) To find the depth of the water in the well, use equation with r_0 = 0.3/2 = 0.15 and k = 66.36 m/d:

$$h_0^2 = H^2 - \frac{Q}{\pi k} Ln\frac{R}{r} = 15^2 - \frac{1576.8}{\pi x 24.9} Ln\frac{254.9}{0.15} = 75.09$$

From which: h = 8.7 m

Then drop in level = drawdown at well face = s_o = 15 – 8.7 = 6.3 m

iv) Suggest type of aquifer natural soil for a permeability of 66.36 m/day from given diagram to be "coarse sand".

v) yield of well for a diameter of 30 cm ought to be between 2000 to 3500 m3/d. Pumping done at a rate of 4320 m3/d which suggests a suitable diameter of 35 cm. Taking this diameter would yield a flow of:

$$Q_o = \frac{\pi k\ H^2\quad h_0^2}{Ln\frac{R}{r_o}} = \frac{\pi x 66.36\ 15^2\quad 8.48^2}{57\ Ln\frac{242.2}{0.15}} = 4322 m3/d$$

Thus a well diameter of 35 cm is suggested for improvement to yield a flow rate of 4322 m3/d (within yield of 3000 to 5000, O.K.).

Example 5.6

A catchment area is undergoing a prolonged rainless period. The discharge of the stream draining it is 140 m^3/s after 15 days without rain, and 70 m^3/s after 45 days without rain. Derive the equation of the depletion curve in the form $Q_t = Q_o * e^{-at}$ and estimate the discharge 90 days without rain (B.Sc., DU, 2012).

Solution

1) Data: values of flow rate Q_a and Q_t, after one month and eight days, Q_{15} = 140, Q_{45} = 70 m^3/s. Q_{90}?
2) Find base flow hydrograph equation using the equation: $Q_t = Q_o * e^{-at}$
   Insert given values in the equation as shown below in equations 1 and 2.
   $140 = Q_o \times e^{-15a}$ (1)
   $70 = Q_o \times e^{-45a}$ (2)
   Dividing equations 1 and 2 to find values of coefficient : a = 0.0231 /day
3) Substitute in one of the equations 1 or 2 to find the value of the primary discharge Q_o as follows:
   $Q_o = 140 \div e\text{-}15x0.0231 = 198\ m^3/s$

Basal flow hydrograph formula becomes: $Q_t = 198 * e^{-0.0231t}$

4) Find rate of the stream after a period of 90 days in the watercourse compensation in the basal flow hydrograph equation obtained in step 4 above: $Q_t = 198 * e^{-0.0231 * t}$, $Q_{90} = 198 * e^{-90 \times 0.0231} = 24.7\ m^3/s$

Example 5.7

The static level of water table in an unconfined aquifer was 33.5m above the underlying impermeable stratum. A 150mm diameter well, penetrating the aquifer to its full depth, was pumped at the rate of 25 litres per second. After several weeks of pumping, the drawdown in observation wells 20m and 50m from the well were 3.55m and 2.27m respectively, and the observed drawdowns were increasing very slowly. (B.Sc., UAE, 1989).

a. Assuming equilibrium conditions, estimate the hydraulic conductivity and transmissivity of the aquifer.
b. Estimate the drawdown just outside the pumped well.
c. What will be the yield of a 300mm diameter well which will produce the same drawdowns just outside the well and at the 50m distance observation well in (ii)? What would be the drawdown at a nearer observation well?

Solution

a) $Q = \frac{\pi k(H^2-h^2)}{ln\frac{R}{r}}$

$$\frac{\pi k(H^2-h^2)}{ln\frac{R}{r}}\Big]_{1st\ well} = \frac{\pi k(H^2-h^2)}{ln\frac{R}{r}}\Big]_{2nd\ well}$$

$$\frac{33.5^2-(33.5-3.55)^2}{ln\frac{R}{20}} = \frac{33.5^2-(33.5-2.27)^2}{ln\frac{R}{50}}$$

$225.2475\, ln\frac{R}{50} = 146.9371\, ln\frac{R}{20}$

$ln\frac{R}{50} = 0.6523\, ln\frac{R}{20}$

$\frac{R}{50} = \left(\frac{R}{20}\right)^{0.6523}$

$R^{0.34766} = 50\left(\frac{1}{20}\right)^{0.6523}$

$\therefore$ R = 279 m

$k = \frac{Q.ln\frac{R}{r}}{\pi(H^2 - h^2)} = \frac{20 \times 10^{-3} ln\frac{279}{20}}{\pi[33.5^2 - (33.5 - 3.55)^2]} = \frac{20 \times 10^{-3} ln\frac{279}{20}}{\pi[225 - (33.5 - 3.55)^2]}$

$= 7.45\times10^{-5}$ m/s = 6.44m/d

T = kH = 6.44×33.5 = 215.7 m^2/d

ii] Depth of water in well, $h^2 = H^2 - \frac{Q}{\pi k} ln\frac{R}{r} = 33.5^2 - \frac{20\times10^{-3}}{\pi\times7.45\times10^{-5}} ln\frac{279}{0.075}$

= 419.7

H = 20.49 m

Drawdown = 33.5 – 20.49 = 13.01 m.

iii] a) $Q = \frac{\pi k(H^2-h^2)}{ln\frac{R}{r}} = \frac{\pi\times7.45\times10^{-5}[33.5^2-(33.5-2.27)^2]}{ln\frac{279}{0.15}} = 4.6\times10^{-3}\, m^3/s$

b) $h^2 = 33.5^2 - \frac{4.6\times10^{-3}}{\pi\times7.45\times10^{-5}} ln\frac{279}{0.15} = 974.3$

h = 31.2 m.

Drawdown = 33.5 – 31.2 =2.3m

Example 5.8

A well of diameter 0.3 m contains water to a depth of 50 m before pumping commences. After completion of pumping the draw-down in a well 20 m away is found to be 5 m, while the draw-down in another well 40 m further away reached 3 m. For a pumping rate of 2500 L/minute, determine:

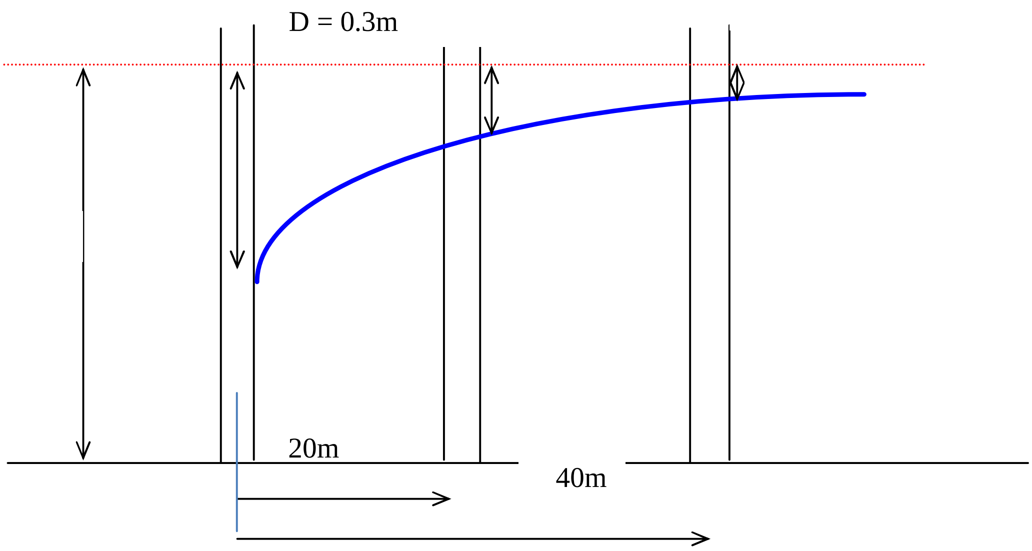
- radius of zero draw-down.
- coefficient of permeability, and
- draw-down in the pumped well (B.Sc., DU, 2013).

Using expected well yield estimates as presented in table (5.1), comment about yield of the well as related to its diameter, & suggest a more suitable well diameter. Explain and validate your answer(B.Sc., DU, 2013) .

$$Q = \frac{\pi k\left(H^2 - h^2\right)}{Ln\frac{R}{r}}$$

Solution

- Given: D= 0.3 m, H = 50 m, r_1 = 20 m, x_1 = 5 m, r_2= 40 m, x_2= 3 m, Q_o = 2500 L/min.



Find $h_1 = h - x_1 = 50 - 5 = 45$ m, and $h_2 = h - x_2 = 50 - 3 = 47$ m.
Use the following equation for both observation wells:

$$Q = \frac{\pi k\left(H^2 - h^2\right)}{Ln\frac{R}{r}} \qquad \therefore \left[\frac{\pi k\left(H^2 - h^2\right)}{Ln\frac{R}{r}}\right]_{\text{ist well}} = \left[\frac{\pi k\left(H^2 - h^2\right)}{Ln\frac{R}{r}}\right]_{\text{2nd well}}$$

By substituting given values into the previous equation, then:

$$\therefore \left[\frac{\left(50^2 - 45^2\right)}{Ln\frac{R}{20}}\right]_{\text{ist well}} = \left[\frac{\left(50^2 - 47^2\right)}{Ln\frac{R}{40}}\right]_{\text{2nd well}}$$

- This yields R = 119.7 m.
- Find the permeability coefficient by using the data of one of the wells.
  Thus, for h = 50 m, ho = 45 m, r = 20 m, R = 119.7 m, Q = 2500*10^{-3}*60*24 = 3600 m^3/day,

$$k = \frac{QLn\frac{R}{r_1}}{\pi\left(H^2 - h_1^2\right)} = \frac{3600Ln\frac{119.7}{20}}{\pi\left(50^2 - 45_1^2\right)} = 4.32 \quad m/d$$

- Depth of the water in the pumped well may be found as:

$$Q_o = \frac{\pi k\left(H^2 - h_o^2\right)}{Ln\frac{R}{r_o}} \qquad \text{Or} \qquad h_0^2 = H^2 - \frac{Q}{\pi k}Ln\frac{R}{r_o} = 50^2 - \frac{3600}{\pi x4.32}Ln\frac{119.7}{0.15}$$

This yields, h = 27 m

Determine the draw-down at the well as:
$r_o = h - h_1 = 50 - 27 = 23$ m.

- From table for a well diameter of 30 cm, yield is 2000 – 3500 m^3/d.
  The amount of water abstracted is Q_o = 2500 L/min = 2500*60*24/1000 = 3600 m^3/d. A better design would be selected a well of diameter of 35 cm (giving a yield of 3683 m^3/d for computed drawdown sat well (O.k. between 3000 - 5000).

$$Q_o = \frac{\pi \times 4.32\left(50^2 - 27^2\right)}{Ln\frac{119.7}{(0.35/2)}} = 3683 \quad \text{cubic meter per day}$$

Example 5.9

a) A well penetrates into an unconfined aquifer having a saturated depth of 100 m. The discharge is 250 litres per minute at 12 m drawdown. Assuming equilibrium flow conditions and a homogeneous aquifer, estimate the discharge at 18 m drawdown. The distance from the well where the drawdown influence are not appreciable may be taken to be equal for both cases. (UAE, 1990).

Solution:

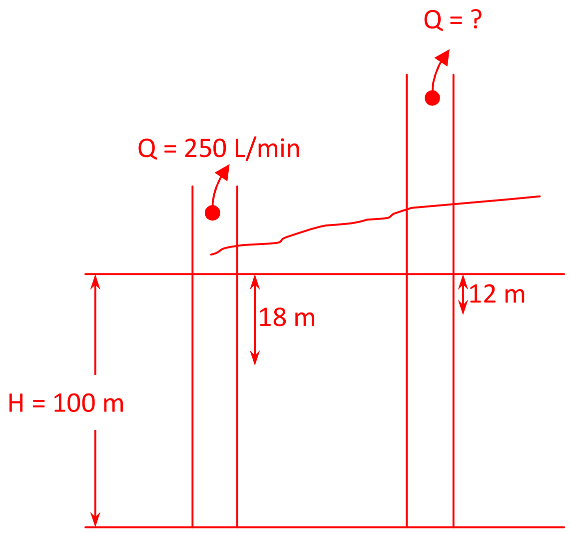
a) – Pollutants. - Difficulty.

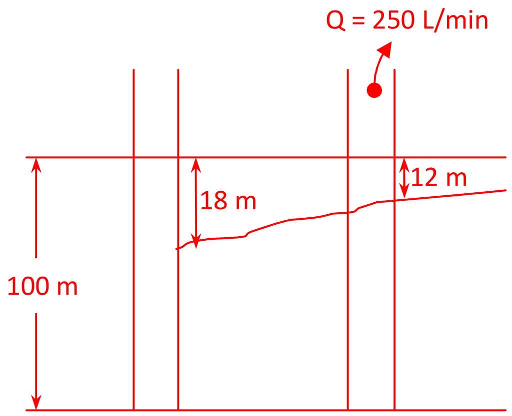
b) $Q = \frac{\pi k\,(H^2 - h_1^{\,2})}{\ln\frac{R}{r_o}}$ $\qquad Q_1 = 250 = \frac{\pi k\,[100^2 - (100-12)^2]}{\ln\frac{R}{r_o}}$

$$\frac{\pi k}{\ln\frac{R}{r_o}} = \frac{250}{(100+88)(100-88)} = \frac{250}{188 \times 12}$$

$$Q_2 = \frac{\pi k}{\ln\frac{R}{r_o}}[100^2 - (100-12)^2] = \frac{250}{188 \times 12}[100^2 - 82^2]$$

$$\frac{250}{188 \times 12} \times 182 \times 18 = 363\ L/min$$





Example 5.10

A 0.3 m diameter well penetrates vertically through an aquifer to an impervious strata which is located 18 m below the static water table. After a long period of pumping at a rate of 1 m^3/min., the drawdown in test holes 14 and 40 m from the pumped well is found to be 2.62 and 1.5 m, respectively.

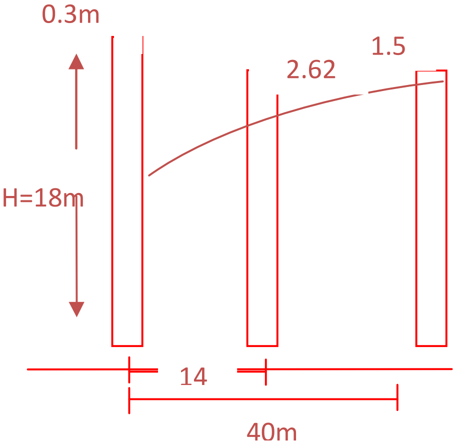
i) Determine coefficient of permeability of the aquifer.
ii) What is the transmissibility of the aquifer?
iii) Compute the specific capacity of the pumped well. (UAE, 1990).

Solution:

a) r, Q, H, T, specific yield storage, lateral extent of aquifer, well

b) $Q = \frac{\pi k(H^2 - h^2)}{ln\frac{R}{r}}$

$$\frac{\pi k(18^2 - [18-2.62]^2)}{ln\frac{R}{14}} (first\ well) = \frac{\pi k(18^2 - [18-1.5]^2)}{ln\frac{R}{40}}$$



$$ln\frac{R}{40} = 0.5917 ln\frac{R}{14}$$

$$R^{0.40627} = \frac{40}{14^{0.5917}} = 8.3926 \rightarrow R = 183.21\ m$$

i] $k = \frac{Q ln\frac{R}{r}}{\pi(H^2 - h^2)}$ $(first\ well) = \frac{\frac{1}{60} ln\frac{183.21}{14}}{\pi(18^2 - 15.38^2)} = 1.56 \times 10^{-4}\ m/s = 13.5\ m/d$

ii] T = kH = 13.5x18 = 243 m^3/m.d

iii] depth in well $h^2 = H^2 - \frac{G}{\pi k} ln\frac{R}{r} = 18^2 - \frac{1}{60\pi x 1.56x10^{-4}} \ln\frac{183.21}{0.15} = 82.28$

h = 9.1 m

drawdown (r) = H –h = 18-9.1 = 8.9m

iv] specific capacity = $\frac{G}{r} = \frac{1}{60x8.9}$ m^2/s

5.2 Theoretical Exercises

1) Outline main differences between confined and unconfined aquifer (B.Sc., DU, 2012).
2) Define the term "**Transmissibility** of aquifer".
3) Define parameters that may influence **yield** of wells.
4) Comment on yield of well compared to its diameter. Give suggestions for improvement?
5) Define factor that may influence yield of wells. (B.Sc., UAE 1989,, UAE 1990, B.Sc., DU, 2012).

   Solution

   Drawdown, Flow conditions, Depth of penetration, Transmissivity, Specific yield, Storage coefficient, Lateral extent of aquifer-, Construction and condition of well.

6) Outline most important factors affecting productivity of a well (B.Sc., DU, 2013).

   Solution

   Most important factors affecting productivity of a well:

   - Lowering of groundwater within aquifer (drawdown aspects).
   - Dimensions of aquifer & its lateral extent.
   - Ground water storage.

- Transmissivity & specific yield or storage coefficient of aquifer.
- Conditions of flow (steady or unsteady).
- Depth of well.
- Establishment of well & methods of construction, properties & condition.

7) In your opinion, what is the most significant source of groundwater pollution in this country? Explain why is groundwater contamination so difficult to detect and clean up? (UAE, 1990).
8) Define parameters shown in Theims equation: (B.Sc., DU, 2012)

$$S_o = \frac{Q_o}{2\pi kH} \ln \frac{R_o}{r} = \frac{Q_o}{2\pi T} \ln \frac{R_o}{r}$$

9) Define terms used in the equation used to estimate rate of constant pumping from a well penetrating an unconfined aquifer (B.Sc., DU, 2011)

$$Q_o = \frac{\pi k\left(H^2 - h_o^2\right)}{Ln\frac{R}{r_o}}$$

Solution

Q_o = Steady state discharge from well, m^3/s.

k = Coefficient of permeability, m/s.

H = Saturated thickness of aquifer, m.

h_o = Depth below original water level at surface of well, m.

R = Radius of zero draw down (effective radius of drawdown), m.

r_o = Radius of well, m.

10) Comment about Theim's equation (equilibrium equation) assumptions (B.Sc., DU, 2012).
11) Write briefly about groundwater in the kingdom of Saudi Arabia with reference to the following: Occurrence, Distribution, Quantity & volumes of aquifers, Quality, Potential hazards & pollution indicators.
12) What are the factors affecting groundwater flow within a basin?
13) What are Dubois's assumptions? How to use them?
14) What is the difference between stable and unstable flow?
15) What is the difference between a water table well and an artesian well? (Draw sketches).

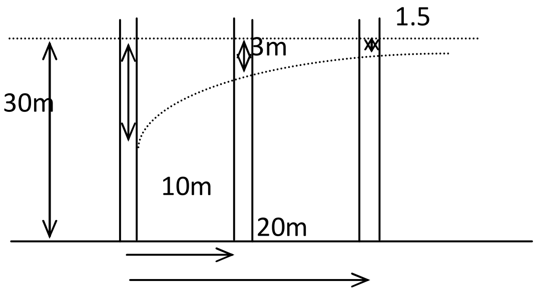
5.3 Problem solving in groundwater

Well yield, drawdown

1) A 30 cm well is pumped at the rate of Q m^3/minute. At observation wells 15 m and 30 m away the drawdowns noted are 75 and 60 cm, respectively. The average thickness of the aquifer at the observation wells is 60 m and the coefficient of its permeability amounts to 26 m/day.
   i) Find the coefficient of **transmissibility** of the aquifer?
   ii) Determine the **rate of pumping** Q.
   iii) Compute **specific capacity** of the well.
   iv) What is the **drawdown** in the pumped well? (UAE, 1989). (Ans. 65 m^2/hr, 1.5 m^3/min, 0.73 m^2/min, 2 m).
2) A 30 cm well penetrates 45 m below the static water table. After a long period of pumping at a rate of 1200 Lpm, the drawdown in the wells 20 and 45 m from the pumped well is found to be 3.8 and 2.4 m respectively.
   a) Determine the **transmissibility** of the aquifer.
   b) What is the **drawdown** in the pumped well? (UAE, 1989). (Ans. 7.1 m^2/hr, 13.5 m).
3) A 30 cm well serves a community of 1100 capita with a water consumption rate of 250 l/day. Under steady-state conditions the drawdown in the well was 1.83 m. The well

penetrates to an impermeable stratum 32 m below the water table of a homogeneous-isotropic unconfined aquifer. Compute the change in the **discharge** in l/s for a well drawdown of 1.83 m if the diameter of the well was: a) 20.0 cm; and b) 50 cm. Assume that the radius of influence in all cases is 760 m. (SQU, 1991).

4) A community of 15,000 capita and fire demand of 35 L/s for six hours is to be served by a 50 cm diameter well. The well is constructed in a confined aquifer with a uniform thickness of 15 m and hydraulic conductivity of 100 m/d. Two observation wells are installed at radial distance of 50 m and 150 m. The drawdowns in the wells are 1.7 m and 1.3 m respectively. Find:
   a) the **discharge** of the well.
   b) water **consumption** (l/c/d).
   c) the **power** needed to lift the water to the ground surface if the original piezometer level is 20 m below the ground surface. (SQU, 1991).
5) Gravity well is 50 cm in diameter. The depth of water in the well is 30 meters before the start of pumping. Upon pumping at a rate of 2,100 liters per minute, Water level into a well located about 10 meters away fell by 3 meters, and in another well 20 meters away it reached 1.5 meters. Find: the zero draw down, permeability coefficient, and the drawdown in the well. Draw cone of depression attributed to pumping of this well. (Ans. 41.5m, 3024 m^3/d, 5.2m).



6) The static level of the surface of the water in an unconfined aquifer is 33.5 meters above the underneath impervious layer. Pumping is conducted at a rate of 20 liters per second in a 150 mm diameter well penetrating through all the depth of the aquifer. After a few weeks of pumping in observation wells at 20 meters and 50 meters distance the water table decreased by 3.55 meters and 2.27 meters, respectively and drawdowns increased gradually and slowly. Assuming equilibrium conditions, find: hydraulic permeability coefficient, drawdown directly outside the pumped well. Draw cone of depression attributed to pumping of this well. How much is the yield from a 300 mm diameter well that can achieve the same reduction in level outside it and at 50 meters from the observation well. Determine the amount of drawdown in the neighboring observation wells?
7) A well of diameter of 0.3 meters was drilled to impervious base in the center of a circular island of radius of one kilometer in a large lake. The well penetrates deeply in a sandstone aquifer which have a thickness of 20 meters which lies below a layer of impermeable clay. Permeability of sandstone equals 20 meters per day. Find steady flow on the assumption that drawdown for the pezometic surface is equal to 2.5 meters in the well. (Assume R_0 = twice distance between aquifer and lake). Comment about yield of well as related to its diameter, and suggest a more suitable well diameter. Explain your answer**.**
8) A fully penetrating well, with an outside diameter of 0.2 m discharges water at a constant rate of 6 cubic meters per minute from an aquifer whose coefficient of transmissivility is

120 square meters per hour. The aquifer is in contact with a lake 1.6 kilometer away and has no other source of supply. What is drawdown at the well surface? (R_0 can be estimated to equal twice the distance between the aquifer and the lake).

9) Tube well 30 cm diameter penetrates an unconfined aquifer. Find the discharge from the tube well on the assumption that the drawdown does not exceed 2 meters, the effective height of the screen under conditions of the above mentioned drawdown is equal to 10 meters, the coefficient of permeability of the aquifer of 0.05 cm/s, and the radius of zero drawdown Ro (effective radius of drawdown) is equivalent to 300 meters.
10) A gravity well of diameter 30 cm, water depth in it 20 meters before pumping is started. When pumping is being done at a rate of 1800 liters per minute, the drawdown in a well 15 meters away is 2.5 m; and in another well 30 meters away is 1.5 m. Find:
    - Radius of zero draw down.
    - The coefficient of permeability, and
    - Drawdown in the well.
    - Give a suggestion for type of aquifer soil with compute permeability.
11) Find amount of water from a well of a diameter of 15 cm penetrating to the end of an unconfined groundwater aquifer at a distance of 30 m from the ground surface, note that its permeability is 3 meters/hour, and the level of drawdown in the well is 2.5 m, and radius at which the level of groundwater vanishes is 400 meters.
12) A well of diameter 30 cm penetrates into groundwater aquifer. Water depth in it reaches 15 meters. The level of fall of water in two observation wells at distances 30 and 60 meters from the well was found to be 1.2 and 0.5 meters, respectively, when the water pumping rate is 4000 liters per minute. Find the permeability coefficient of the basin and the level of drawdown in the well after pumping.

Aquifer recharge

13) A well was drilled an impervious base in center of a circular island of diameter 1.5 km in a large lake. The well penetrates totally in the sandstone aquifer which is 18 meters thick located under a layer of impervious clay. Permeability of sandstone equals 15 meters per day. Find stable flow if the decline in pesimoetric surface should not exceed 2 meters in a well of diameter 0.3 meters.
14) Suppose there are two canals, at different levels, separated by a strip of land 900 meter wide, of permeability that reaches 0.3 m/hr. If one of the canals is 1.3 m higher than the other and the depth of the aquifer is 15 m below the lower canal to an impermeable base, find inflow into, or abstraction from, each canal per unit width. take annual rainfall as 2.1 m/annum and assume 85 percent infiltration.
15) A rain gauge in a particular area showed that the average annual rainfall was 610 mm. 75 percent of this rain seeps into the ground. There are two channels separated by a piece of land of width 1 kilometer and permeability 0.35 m/h, one of the canals is higher than the other by about 1.2 meters. Geological surveys in the region pointed out to the presence of a groundwater basin under the piece of land with an average depth of 10 meters. Find the rate of outflow from each channel to the aquifer.

Chapter Six
Surface runoff

6.1 Runoff

Runoff is that part of the precipitation, as well as any other flow contributions, which appears in surface stream of either perennial or intermittent form. It is the flow collected from a drainage basin or water shed, and it appears at an outlet of the basin. Specifically, it is the flow, which is the stream flow unaffected by artificial diversions, storage or any works of man in or on the stream channel, or in the drainage basin or water shed.

Runoff divisions according to source of flow [1,2,15] include: surface flow (runoff), sub surface flow (interflow, sub surface storm flow, storm seepage) and groundwater flow (groundwater runoff).

Example 6.1

An unregulated river has monthly mean flows (in m^3/s) as presented in the table (B.Sc., DU, 2013).

Table: Monthly records of stream flow.

Month	Monthly mean flow, m^3/s
January	5.4
February	8.3
March	9.1
April	8.8
May	6.3
June	6.9
July	10.2
August	13.7
September	19.4
October	16.7
November	11.0
December	21.9

i) Allowing compensation water of 4.0 m^3/s and reservoir losses of 0.5 m^3/s, what storage capacity of reservoir is required to ensure that, on average, no water is spilled? Assume 30-day months.

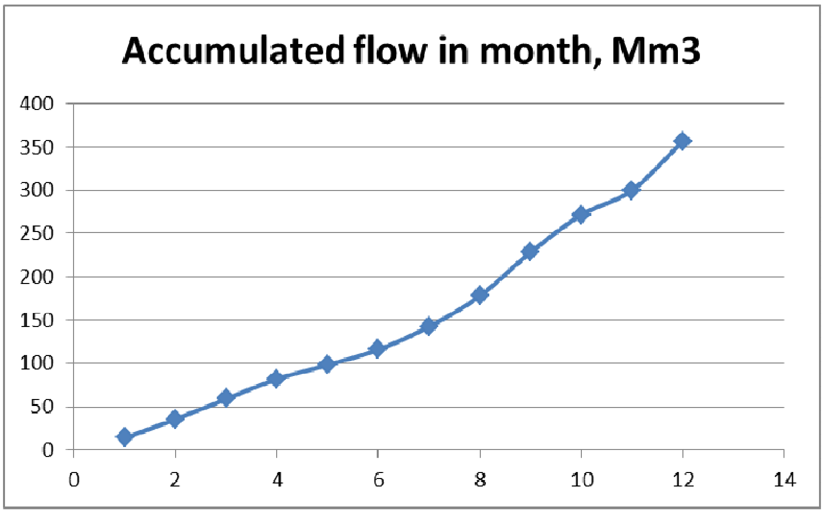
ii) What would the average net yield of the reservoir then be? (Hint: average net yield of reservoir = demand – compensation – losses).

Solution

- Data: regular consumption of 230 m^3/min, & data of monthly water flow.
- Find cumulative total flow as shown in the following table:
- Draw mass curve for data by plotting cumulative flow values as a variable with time.

Month (1)	Flow, m^3/s (2)	Flow, m^3/day (3) = col (2)*60*60*24*30	Accumulated flow in month, m^3 (4)
Jan	5.4	13996800	13996800
Feb	8.3	21513600	35510400
Mar	9.1	23587200	59097600
April	8.8	22809600	81907200
May	6.3	16329600	98236800
June	6.9	17884800	1.16E+08
July	10.2	26438400	1.43E+08
Aug	13.7	35510400	1.78E+08
Sept	19.4	50284800	2.28E+08
Oct	16.7	43286400	2.72E+08
Nov	11	28512000	3E+08
Dec	21.9	56764800	3.57E+08

- Determine monthly flow (column 3) by multiplying each value in column (2) by 60*60*24*30 to obtain flow in m^3 per month, taking a 30day month as assumed.
- Find accumulated flow as shown in column (4).
- Draw mass curve of reservoir.
- Draw demand line for no water spillage on curve.
- Find storage for no spillage as maximum ordinate between mass curve and demand = $66*10^6$ m^3 = 66 Mm^3.
- Determine demand = $356.9*10^6/12 = 29.74*10^6$ m^3/month = $29.74*10^6/(30*24*60*60)$ = 11.5 m^3/s
- Compute average net yield of reservoir = demand – compensation – losses = 11.5 – 4 – 0.5 = 7 m^3/s.



6.2 Flow mass curve (Ripple diagram, S-curve)

This is a graph of the cumulative values of hydrological quantity (such as: runoff) plotted against time or data. Mass curve represents studying the effects of storage on the regime of a stream and of determining the regulated flow by means of a flow summation curve. Mass curve is a curve on which the ordinate of any point represents the total amount of water that has flowed past a given station on a stream during the length of time represented by the magnitude of the abscissa to the same point on the curve.

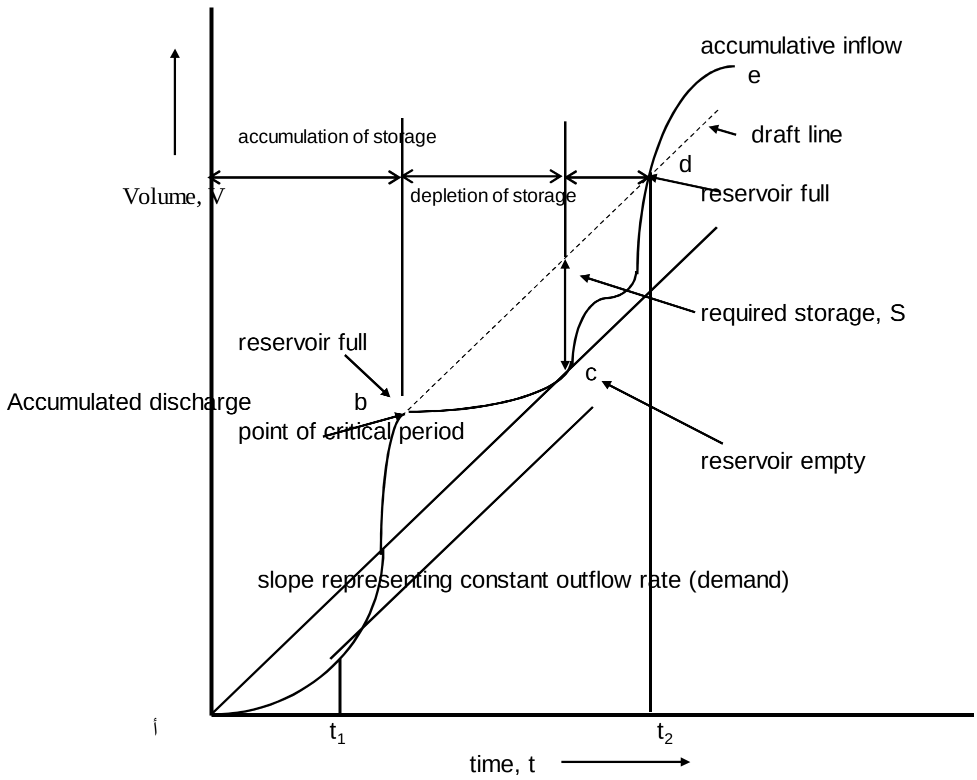


Fig. 7.7 Mass curve or Rippl diagram

Example 6.2

1) Outline benefits of a mass curve (flow duration curve or Rippl diagram).
2) A water reservoir is designed to collect water from the adjacent catchment basin & to regulate water use across an average regular flow of 230 cubic meters per minute. The table below shows the monthly records of the stream flow. Find amount of **storage** needed to keep up with regular consumption assuming no loss of water (B.Sc., DU, 2013).

Monthly records of stream flow.

Month	Volume of water, million cubic meter
January	8
February	65
March	45
April	35
May	25
June	12
July	2
August	3
September	9
October	45
November	67
December	77

Solution

- Data: regular consumption of 230 m^3/min, & data of monthly water flow.
- Find cumulative total flow as shown in the following table:
- Draw mass curve for data by plotting cumulative flow values as a variable with time.

Month	Volume of water (million cubic meter)	Cumulative Volume of water (million cubic meter)
1	8	8
2	65	73
3	45	118
4	35	153
5	25	178
6	12	190
7	2	192
8	3	195
9	9	204
10	45	249
11	67	316
12	77	393

- Find the value of the annual use rate (for the month of December) = 230 (m^3/min) × 60 (minutes/hour) × 24 (hours/day) × 365 (day/year) = 120.89 × 10^6 m^3/year = 121 million m^3/year.
- Draw draft line of uniform use from the point of origin to the point (a) on the mass curve.
- Draw a line parallel to the draft line from the point where the reservoir is full (b), & then find the value of minimum required storage for the reservoir to keep pace with consumption = 20 × 10^6 m^3.

Example 6.3

The peak water consumption on the day of maximum water usage as follows: (B.Sc., UAE, 1989).

Time	L/s	Time	L/s
Midnight	220	13	640
1	210	14	630
2	180	15	640
3	140	16	640
4	130	17	670
5	120	18	740
6	200	19	920
7	350	20	840
8	500	21	500
9	600	22	320
10	640	23	280
11	700	Midnight	220
Noon	660		

i. Calculate hourly cumulative consumption values.
ii. Plot (i) to a mass diagram curve.
iii. What is the constant 24 hour pumping rate.
iv. Compute required storage capacity to equalize demand over the 24 hour period.

Solution

a) A graph of cumulative values of hydrologic quantities was plotted against time or data: Reservoir condition, Demand, Spillage

b)

Time	Hourly consumption		Comulative consumption
	L/s	$L\times10^3$	$L\times10^6$
Midnight	220	792	0.792
1	210	756	1.548
2	180	648	2.196
3	140	504	2.7
4	130	468	3.168
5	120	432	3.6
6	200	729	4.32
7	350	1260	5.58
8	500	1800	7.38
9	600	2160	9.54
10	640	2304	11.844
11	700	2520	14.364
12	660	2376	16.74
13	640	2304	19.044
14	630	2268	21.312
15	640	2304	23.616
16	640	2304	25.92
17	670	2412	28.32
18	740	2664	30.996
19	920	3312	34.308
20	840	3024	37.332
21	500	1800	39.132
22	320	1152	40.284
23	280	1008	41.292
Midnight	220	792	42.084

11590/24= 487

Average $=\frac{42084}{24\times3600} = 487\ L/s$

6.3 Hydrograph

A hydrograph is a graph showing change of runoff volume (or stage, flow or discharge, velocity, or any other properties of water flow) w.r.t. time.

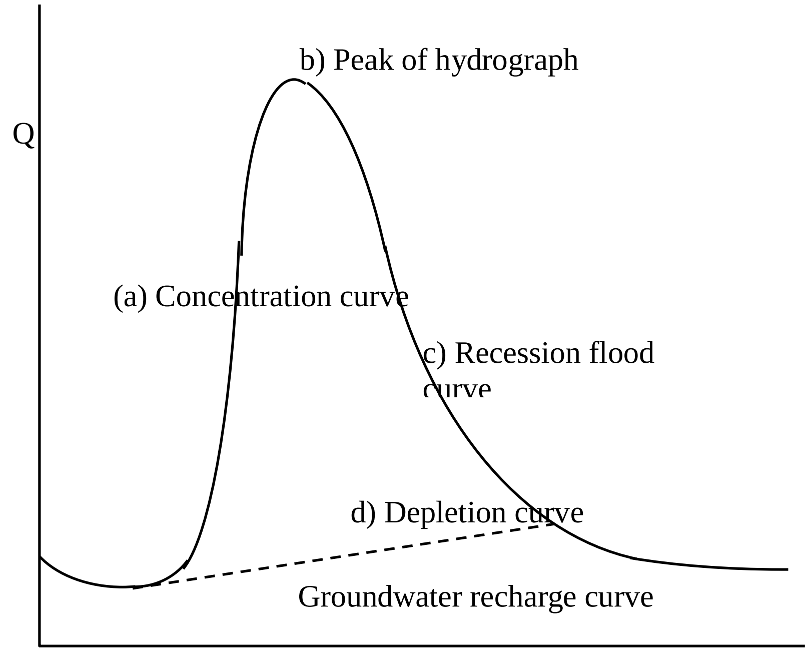
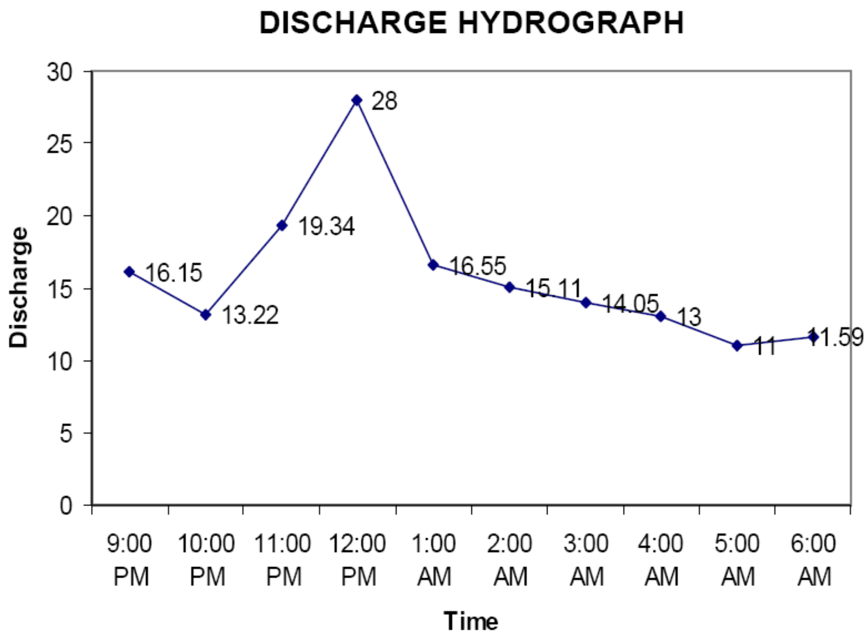


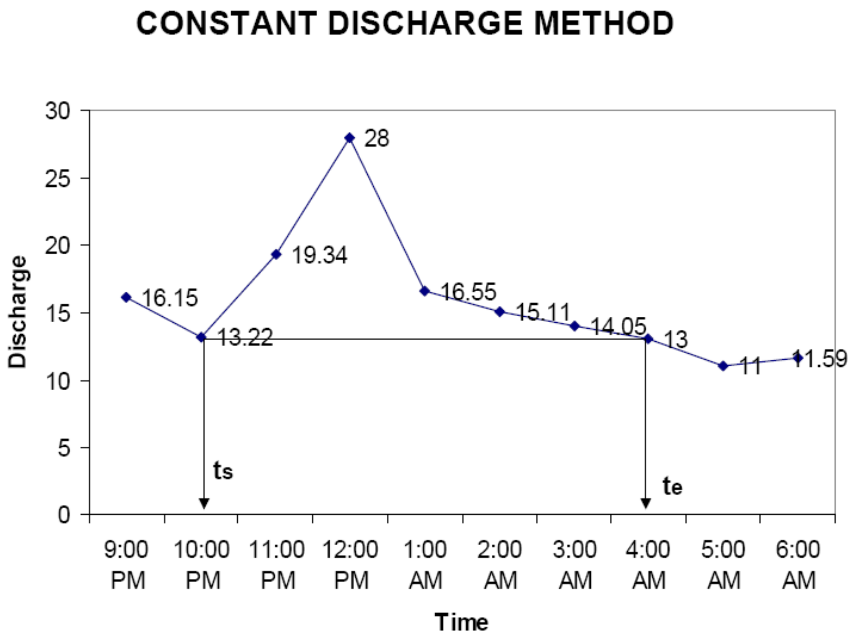
Fig. 6.2 Divisions of hydrograph

Example 6.4

The ordinates of discharge hydrograph measured on a 1-hour interval at Lahat Bridge. Pari river, Ipoh.

Ordinate Number	Accumulated Time	Discharge (m^3/s)
1	9 pm	16.15
2	10 pm	13.22
3	11 pm	19.34
4	12 pm	28.00
5	1 am	16.55
6	2 am	15.11
7	3 am	14.05
8	4 am	13.00
9	5 am	11.00
10	6 am	11.59





Constant Discharge Method

For t < ts	Qb = Q
For ts ≤ t ≤ te	Qb = qs
For t > te	Qb = Q

Direct Runoff = Total Runoff - Base Flow

Ordinate Number	Accumulated Time	Discharge (m3/s)	Base flow (m^3/s)	Direct Runoff (m^3/s)
1	9 pm	16.15	16.15	0
2	10 pm	13.22	13.22	0
3	11 pm	19.34	10.29	9.05
4	12 pm	28.00	7.36	20.64
5	1 am	16.55	16.55	0
6	2 am	15.11	15.11	0
7	3 am	14.05	14.05	0
8	4 am	13.00	13.00	0
9	5 am	11.00	11.00	0
10	6 am	11.59	11.59	0

Equivalent Runoff Depth

Equivalent runoff depth = Total Direct Runoff X Time (s) + Area

Equivalent runoff depth

$= (26.95 \times 60 \times 60)\ m^3\ /\ (271 \times 10^6)\ m^2$

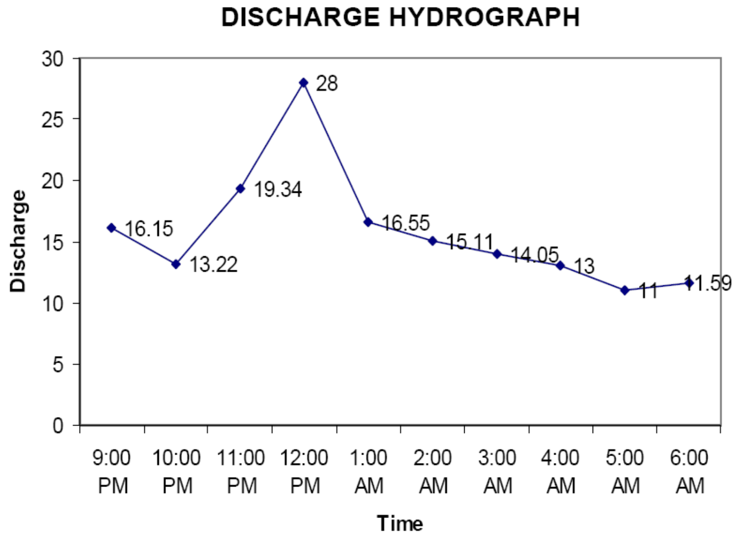
$= 0.36 \times 10^{-3}$ m

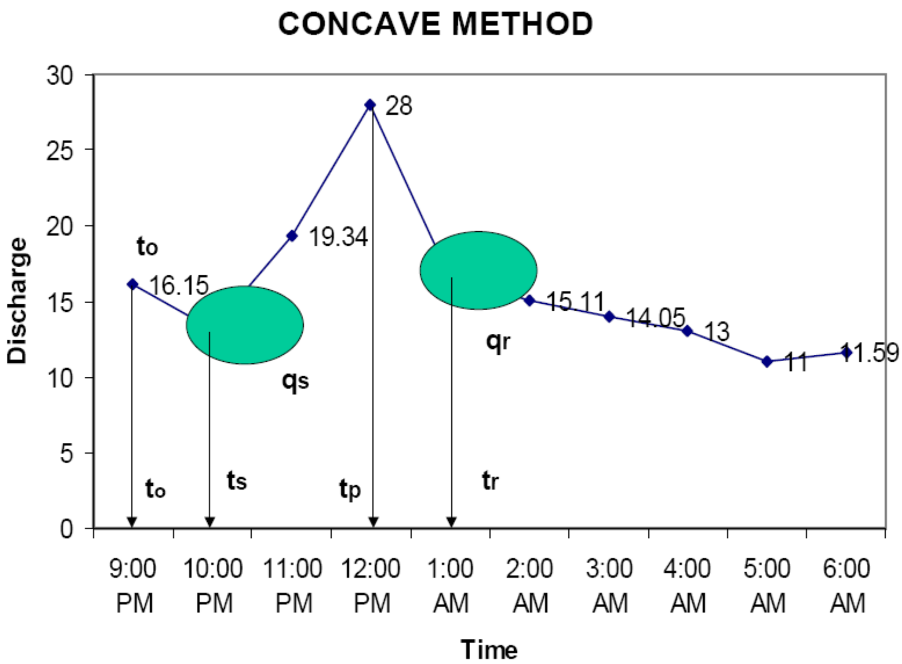
$= 0.36 \times 10^{-3}$ m x 100 cm/m

= 0.04 cm

Example 6.5

Solve the previous problem using the Concave Base Flow Method





Important data taken from the hydrograph

T_s = 10.00 pm Q_s = 13.22 m^3/s
T_r = 1.00 am Q_r = 16.55 m^3/s
T_o = 9:00 pm Q_o = 16.15 m^3/s
T_p = 12:00 pm

Notes: Q_b at tp is taken as q_m

$$q_b = \begin{cases} q & \text{for } t < t_s \\ q_s + (t - t_s)[(q_s - q_o)/(t_s - t_o)] & \text{for } t_s < t \le t_p \\ q_m + (t - t_p)[(q_r - q_m)/(t_r - t_p)] & \text{for } t_p < t \le t_r \\ q & \text{for } t_r < t \end{cases}$$

Example of calculation at 11:00 pm

Q_b = 13.22 + (11 – 10) [(13.22 – 16.15) / (10 – 9)] = 10.29 m^3/s

Example of calculation at 1:00 am

Q_b = = 7.36 + (1am – 12 am) [(16.55-7.36)/(1am – 12 am)] = 16.55 m^3/s

Ordinate Number	Accumulated Time	Discharge (m3/s)	Base flow (m^3/s)	Direct Runoff (m^3/s)
1	9 pm	16.15	16.15	0
2	10 pm	13.22	13.22	0
3	11 pm	19.34	10.29	9.05
4	12 pm	28.00	7.36	20.64
5	1 am	16.55	16.55	0
6	2 am	15.11	15.11	0
7	3 am	14.05	14.05	0
8	4 am	13.00	13.00	0
9	5 am	11.00	11.00	0
10	6 am	11.59	11.59	0

Equivalent Runoff Depth

Equivalent runoff depth = Total Direct Runoff X Time (s) + Area

Equivalent runoff depth

= (26.95 x 60 x 60) m^3 / (271 x 10^6) m^2

= 0.36 x 10^{-3} m

= 0.36 x 10^{-3} m x 100 cm/m

= 0.04 cm

The general shape of the hydrograph of any ri

Example 6.6

A rain of 35mm fell on a drainage basin during a one-hour period beginning 01-00 hr. The drainage area is 78.2 km^2. The Following table lists the measured discharge from the area with respect to time: (B.Sc., UAE, 1989).

Hour	Discharge (m3/s)	Hour	Discharge (m3/s)
0	0	10	2.83
1	1	11	2.38
2	1.2	12	2.02
3	2.97	13	1.76
4	24.1	14	1.64
5	51.5	15	1.47
6	32.3	16	1.39
7	11.2	17	1.27
8	5.95	18	0
9	3.77		

i. Develop a one hour unit hydrograph.

ii. Compute and plot the hydrograph of surface runoff for two periods of heavy rain occurring:
First storm: of 100mm rain between midnight and 02-00 hr; and 40mm rain between 02-00 and 03-00 hr.
Second storm: of 89mm rain between 04-00 and 05-00 hr. Assume a constant loss rate of 18mm and a constant base flow of 8m^3/s
Comment about your graph.

Solution

a) A hydrograph of direct runoff resulting from 1mm of effective rainfall generated evenly over the basin area at a uniform rate.
- Uniform effective rainfall.
- Uniform distribution over area.
- Constant time duration
- Ordinate α Q
- Reflects physical characteristics of basin.

b) $Average\ Q = \frac{148.75}{18} = 8.264\ m^3/s$

Total runoff = Q_a.t = 8.264×18 (hr)×3600 = 535500 m^3
Measured discharge is to be divided by 6.85 to obtain UH

Time	m^3/s	UH, m^3/s/m	Time	Effective rainfall×UH			Base flow, m^3/s	Total rainfall, m^3/s
				82×UH	22×UH	71×UH		
0	0	0	24	0			8	8
1	1	0.15	1	12.3			8	20.3
2	1.2	0.18	2	14.76	0		8	22.76
3	2.97	0.43	3	35.26	3.3		8	43.56
4	24.1	3.52	4	288.64	3.96	0	8	300.6
5	51.5	7.5	5	615	9.46	10.65	8	643.11
6	32.3	4.7	6	385.4	77.44	12.78	8	483.95
7	11.2	1.6	7	131.2	165	30.53	8	334.73
8	5.95	0.87	8	71.34	103.4	249.92	8	432.66
9	3.77	0.55	9	45.1	35.2	532.5	8	620.8
10	2.83	0.41	10	33.62	19.41	333.7	8	394.44
11	2.38	0.35	11	28.7	12.1	113.6	8	162.4
12	2.02	0.29	12	23.78	9.02	61.77	8	102.57
13	1.76	0.26	13	21.32	7.7	39.05	8	76.07
14	1.64	0.24	14	19.68	6.38	29.11	8	63.17
15	1.47	0.21	15	17.22	5.72	24.85	8	55.79
16	1.39	0.2	16	16.4	5.28	20.59	8	50.27
17	1.27	0.19	17	15.58	4.62	18.46	8	46.66
18	0	0	18	0	4.4	17.04	8	29.44
			19		4.18	14.91	8	27.09
			20		0	14.2	8	22.2
			21			13.49	8	21.49
			22			0	8	8

Example 6.7

Draw the Unit Hydrograph for a river which flows in a midsize catchment of 120 km^2. After a 3-hour storm, the following flow hydrograph was recorded at the catchment outlet flow station. Assume a constant base flow of 10 m^3/s

Time (hr)	Flow Hydrograph (Q) (m^3/s)
0	10
3	20
6	35
9	50
12	70
15	50
18	35
21	10

Time (h)	Flow Hydrograph (Q) (m^3/s)	Base flow (m3/s)	Ordinates of DRH (m^3/s)		Ordinates of 3-hr UH (m^3/s)
0	10	10	0.0		0.0
3	20	10	10.0		5.0
6	35	10	25.0	/ ER	12.5
9	50	10	40.0		20.0
12	70	10	60.0		30.0
15	50	10	40.0		20.0
18	35	10	25.0		12.5
21	10	10	0.0		0

$\sum$ DRH = 200 m^3/s

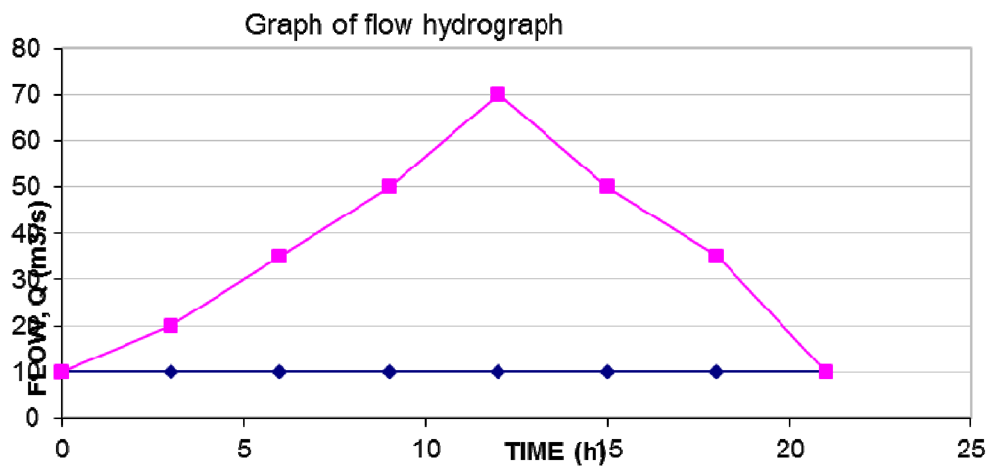
Volume of Direct Runoff Hydrograph (DRH) = 60 X 60 X 3 X 200 = 2.16 Mm^3

Drainage Area = 120 km^2 = 120 X 10^6 m^2

Runoff Depth = Effective Rainfall (ER) = rainfall excess =

= Volume of DRH / Area = (2.16 X10^6) / (120 X10^6) 0.018 m = 1.8 cm

Approximately 2cm

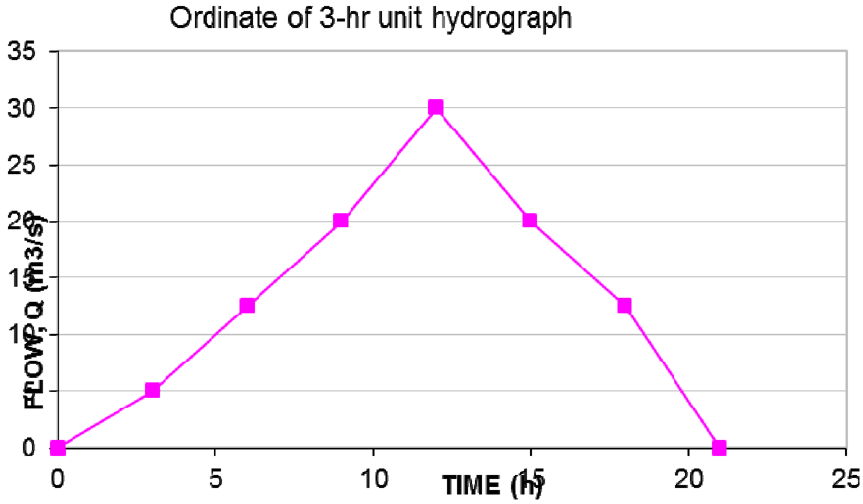


Check Area under UH = 1 cm over catchment area

Ordinates of 3-hr UH (m^3/s)
0.0
5.0
12.5
20.0
30.0
20.0
12.5
0

$\sum$ DRH = 100 m^3/s

Volume = 60 x 60 x 3 x 100 km^2 = 1.08 x 10^6 m^3
Drainage area = = 120 km^2 = 120 x 10^6 m^2
Runoff Depth = Effective Rainfall (ER) = rainfall excess =
= Volume of DRH / Area = (1.08 x 10^6) / (120 X10^6) = 0.01m = 1.0 cm (OK)



6.4 Theoretical Exercises

1) Write at length on each of the following: surface flow, subsurface and base flow, catchment area and use of radioactive materials.
2) Indicate ways used to measure surface flow? Which one would be preferred?
3) What are the assumptions included in the rational formula to estimate surface runoff?
4) Define mass curve "Rippl diagram". What information does it provide? (B.Sc., UAE, 1989).
5) Outline benefits of a mass curve (flow duration curve or Rippl diagram) (B.Sc., DU, 2013).
6) What is meant by "Unit Hydrograph"? Indicate assumptions involved in the hydrograph theory. (B.Sc., UAE, 1989).
7) Write briefly about each of: calibration curve, Rippl curve, and unit hydrograph.
8) How do you calculate peak flows upon availability and unavailability of measurements?
9) Write at length on each of the following: peak flows, and hydrograph.

10) What are the sections of a hydrograph? Indicate methods of its analysis?
11) What are the ways used to separate base flow in a hydrograph?
12) Write a detailed report on each of: unit hydrograph, instantaneous unit hydrograph, artificial water curve.

6.5 Problem solving in surface runoff

1) Suppose that the gauge shows a rise at the rate of 0.2 m/hr during a discharge measurement of 100 m^3/s and the channel is such that this rate of rise may be assumed to apply to 1000 m reach of river between the measurement site and the reach control. let the average width of the channel in the reach be 100 m, find the rate of change of storage, and discharge measurement to be plotted on the rating curve**.**
2) A river discharge measurement made during a flood indicated Qa = 2500 cubic meters per second. During the measurement, which took two hours, the gauge height increased from 30.2 meters to 30.4 meters. Level readings taken at water surface 340 meters upstream and 260 meters downstream of the observation site differed by 100 mm. the river was 350 meters wide with an average depth of 3 meters at the time of measurement. At what coordinate should the measurements be plotted on the rating curve.
3) A water reservoir is designed to collect water from the adjacent catchment basin and to regulate water use across an average regular flow of 8000 cubic meters per hour. The following table shows the monthly records of the stream flow. Find amount of storage needed to keep up with regular consumption assuming no loss of water

Month	Volume of water (million cubic meter)	Month	Volume of water (million cubic meter)
January	7	February	21
March	15	April	14
May	10	June	5
July	1	August	1
September	4	October	14
November	26	December	32

4) A water reservoir is designed to collect water from the adjacent catchment basin and to regulate water use across an average regular flow of 250 cubic meters per minute. The following table shows the monthly records of the stream flow. Find amount of storage needed to keep up with regular consumption assuming no loss of water.

Month	Volume of water (million cubic meter)	Month	Volume of water (million cubic meter)
January	5	February	10
March	10	April	10
May	10	June	20
July	30	August	40
September	60	October	80
November	10	December	5

1) A catchment area is undergoing a prolonged rainless period. The discharge of the stream draining it is 140 m^3/s after 15 days without rain, and 70 m^3/s after 45 days without rain. Derive the equation of the depletion curve in the form $Q_t = Q_o*e^{-at}$ and estimate the discharge 90 days without rain. (ans. $Q_t = 198 * e^{-0.0231t}$,24.7 m^3/s).
2) A catchment area is undergoing a prolonged rainless period. The discharge of the stream draining it is 100 m^3/s after 10 days without rain, and 50 m^3/s after 40 days without rain. Derive the equation of the depletion curve and estimate the discharge 120 days without rain. (ans. α = 0.0231 /day, $Q_t = 126.e^{-0.0231t}$, Q_t = 7.9 m^3/s)
3) A catchment area is undergoing a prolonged rainless period. The discharge of the stream draining it is 4100 m^3/min after ten days without rain, and 1200 m^3/min after one month without rain. Find:
   - The equation of depletion curve.
   - Estimate the discharge after a period of four months, and a period of six months without rain.
   - Draw depletion curve to scale.
4) A reservoir of water is built to collect the amount of rain water falling in the neighboring basin and to organize a regular supply at a flow rate of 9000 cubic meters an hour. Records of stream flow indicated the monthly data listed in the following table. Find amount of storage required for organizing consumption (assuming no loss of water).

Month	Volume of water, million m^3
January	10
February	24
March	18
April	17
May	13
June	8
July	4
August	4
September	7
October	17
November	29
December	35

5) Define **mass curve** “Rippl diagram”. What information does it provide? The peak water consumption on the day of maximum water usage as follows:

Time	L/s	Time	L/s
Midnight	220	13	640
1	210	14	630
2	180	15	640
3	140	16	640
4	130	17	670
5	120	18	740
6	200	19	920
7	350	20	840
8	500	21	500
9	600	22	320
10	640	23	280
11	700	Midnight	220
Noon	660		

v. Calculate hourly cumulative consumption values.
vi. Plot (i) to a mass diagram **curve**.
vii. What is the constant 24 hour **pumping rate**.
viii. Compute required **storage** capacity to equalize demand over the 24 hour period. (ans. 487 L/s).

6) A reservoir is designed to collect water precipitated in the adjacent watershed basin adjacent to regulate supply with an average regular flow equal to 284 cubic meters per minute. The following table shows monthly capacity records of the stream in millions cubic meters. Find amount of storage needed to cope with regular consumption assuming no loss of water.

Month	volume of water (million cubic meters)	month	volume of water (million cubic meters(
January	7.4	February	49.4
March	31.1	April	34.6
May	29.6	June	8.6
July	2.5	August	1.2
September	18.5	October	58
November	76.5	December	82.7

13) Measuring the flow of a river during the flood has shown that Qa = 2700 cubic meters per second. During the measurement, which lasted for two hours, the level increased from 40.48 meters to 40.36 meters. Readings on the surface of the water level at distances of 390 meters and 310 meters upstream and downstream from the observation site differed by about 100 mm. the river width is 400 meters, and its average depth is 3.5 meters during the instant of measurement. Find coordinates of the point that should be taken for measurements in the calibration curve. (Ans. 40.42, 2639).

14) Flow rate in a stream discharging water shed runoff is 50 cubic meters per second after five days without rain. The flow rate in the stream reaches half that amount after 20 days without rain. Determine the equation of basal flow hydrograph. Find the amount of flow rate after a period of six months in the watercourse.

15) The rate of flow in a water course discharging an water shed is 3950 m^3/min after ten days of no rain, and the flow rate is 1190 m^3/min after one month with no rain. Draw the time hydrograph for base flow baseband; and find the amount of flow rate after three months and a five-month period in the watercourse. (Ans. 0.54, 0.015 m^3/s)

16) Calculate and draw one-hour unit hydrograph for a certain area and noting that the discharge area is 70 square kilometers and the runoff from one peak for a precipitation of the 20 mm as represented in the following table:

Time, hr	Measured runoff, m^3/s
0	0
1	3.8
2	11.2
3	12.3
4	11.1
5	8.2
6	5.2
7	3.6
8	3.2
9	2.8
10	2.6
11	2.3
12	2.2
13	2.1
14	2.0
15	1.9
16	1.8
17	1.7
18	1.6
19	1.5
20	1.4
21	0

17) Calculate and draw one-hour unit hydrograph for to a certain area noting that 35 mm of rain fell in a discharge area of 78.2 square kilometers over a period of one hour started at 01:00. The following table shows the measured runoff through the area in the unit of time:

Time, hr	Measured flow, m^3/s	Time, hr	Measured flow, m^3/s
0	0	10	2.83
1	1	11	2.38
2	1.2	12	2.02
3	2.97	13	1.76
4	24.1	14	1.64
5	51.5	15	1.47
6	32.3	16	1.39
7	11.2	17	1.27
8	5.95	18	0
9	3.77		

Chapter Seven

General exercises

7.1 Complete missing titles

a) **Complete missing titles by using the following words and phrases** (**Cyclonic precipitation. Relative humidity. Residence time. Unconfined aquifer. Depression storage. Speed. Detention storage**) (B.Sc., DU, 2012)

1) When rainfall is more than infiltration, evaporation and evapotranspiration, ponds gather in low-lying areas representing **depression storage**.
2) Filling of ponds and depressions Leads water to flood on the surface of the earth representing **detention storage**.
3) **Residence time** is the average duration for a water molecule to pass through a subsystem of the hydrologic cycle.
4) **Relative humidity** describes the ability of air to absorb additional moisture at a given temperature.
5) In absence of other factors tending to influence wind, it should be expected that its direction would be from areas of high pressure towards areas of low pressure and that its **speed** would vary with the pressure gradient.
6) **Cyclonic precipitation** is linked to passage over low temperature areas or altitude, resulting in lifting of hot air masses over cold masses.
7) Dupuit assumptions are used to get an approximate solution for uni-dimensional flow in an **unconfined aquifer**.

7.2 True/false sentences

b) **Indicate whether the following sentences are true (T) or false (F):** (B.Sc., DU, 2012)

1) The intensity and frequency of the hydrological cycle is independent of geography and climate. (**F**)
2) The role of applied hydrology is to provide guidance for planning and management of water resource. (**T**)
3) Earth's rotation affects movement of wind and rotation of seasons. (**T**)
4) Trees reduce wind speeds and cool the air as they lose moisture and reflect heat upwards from their leaves. (**T**)
5) Frost or ice is dew falling from the sky and freezes on the ground. (**T**)
6) Rate of evaporation decreases as the specific gravity increases. (**T**)
7) Infiltration devices estimate quality of infiltration rather than the quantity. (**T**)
8) A confined or artesian aquifer is one that is separated from the surface by an aquiclude or aquitard. (**T**)

c) **Indicate whether the following sentences are true (T) or false (F):** (B.Sc., DU, 2011)

1) Hydrology concerns quantity and quality of moving water accumulating on land, soil & rock adjacent to the surface. (**T**)
2) At night, treetops act as radiating surfaces, and the soil beneath is protected from excessive heat losses. (**T**)
3) In a large city, the amount of heat which is produced annually roughly equals the solar radiation reaching an equivalent area. (**F**)
4) Winds are mainly the result of horizontal differences in pressure. (**T**)
5) Thiessen method is suitable to find number of medium height to a particular area served by a network of fixed stations in number and positions. (**T**)
6) Method of isohyets maps give results close to those obtained by the Thiessen network method. (**T**)
7) Intensity of rainfall indicates quantity of rain falling in a given time. (**T**)
8) Clouds slow up the process of evaporation. (**T**)
9) Rate of evaporation is more for salt water than for fresh water. (**F**)
10) The role of applied hydrology is to provide guidance for planning and management of water resource. (**T**)

7.3 Underline the best answer

d) **Underline the best word or phrase (between brackets) to offer a useful sentence.** (B.Sc., DU, 2011)

1) (**Residence time**/Time of concentration/Rainfall duration) Average travel time for water to pass through a subsystem of the hydrologic cycle.
2) (**Relative humidity** /Dew point/Humidity) is the ratio of amount of moisture in a given space to the amount a space could contain if saturated.
3) A (**psychrometer**/barometer/desiccant) is an instrument used to determine the value of humidity..
4) Actinometer and Radiometer are general names for instruments used to measure (**intensity**/duration/frequency) of radiant energy.
5) Winds are mainly the result of (vertical/**horizontal** /direct) differences in pressure..
6) An instrument for measuring the speed or force of the wind is called (wind vane/**anemometer**/pyranometer).
7) One of the most important reasons leading to condensation of vapor is (heating by air masses mix/ Dynamic or adiabatic heating/**Contact and radiational cooling**).
8) Moist air moving up the side of a mountain facing the prevailing wind causes precipitation to fall in a process known as(conventional/**orographic**/Cyclonic) lifting.
9) One of the factors that influence the measurement of rainfall, especially solid part, is (**wind**/pressure/latitude).
10) Of appropriate recommendations to determine the number of monthly rain gauge stations those proposed by (**Bleasdale**/Buys Ballot/Thiessen).

e) **Underline the best word or phrase (between brackets) to offer a useful sentence.** (B.Sc., DU, 2012)

11) (**Orographic precipitation** / Conventional precipitation / Cyclonic precipitation) occurs due to obstruction of topographical barriers (mountains, natural hills) for

winds laden with moisture and its mechanical lifting to top layers and then its expansion & cooling resulting in rainfall.

12) (**Horton**/ Penman / Agot) equation shows a mathematical method to estimate the infiltration capacity curve.
13) **Φ - index** / W-index / Antecedent Precipitation Index) is that rate of rainfall above which the rainfall volume equals the runoff volume.
14) (**Water-bearing layers** / Man-made reservoirs / Cones of depression) are geological features with permeability and they have components that allow significant movement of water through them.
15) (**Meteoric water** / Juvenile water /Magmatic water) denotes water in or recently from the atmosphere.

7.4 Rearrange groups

f) Rearrange group (I) with the corresponding relative ones of group (II) in the area allocated for the answer in table (1). (B.Sc., DU, 2012)

Table (1) Matching of relevant words or phrases..

Group (I)	Rearranged group (II)	Group (II)
Hydrology	**Water science**	Radiometer
Holton	**Infiltration**	Baric
Psychrometer	**Humidity**	Penman
Connate water	**Fossil water**	Unconfined
Condensation	**Contact cooling**	Water science
Perched aquifer	**Unconfined**	Limestone
Actinometer	**Radiometer**	Fossil water
Evapotraspiration	**Penman**	Infiltration
Karst	**Limestone**	Contact cooling
Buys-Ballot	**Baric**	Humidity

g) Rearrange group (I) with the corresponding relative ones of group (II) in the area allocated for the answer. (B.Sc., DU, 2011)

Group (I)	Rearranged group (II)	Group (II)
Humidity	**Psychrometer**	Rainfall depth
Contact cooling	**Dew**	Convective precipitation
Acinometer	**Radiant energy**	Anemometer
Convectional precipitation	**Convective precipitation**	Hygrometer
Wind speed	**Anemometer**	Frontal precipitation
Wind direction	**Wind vane**	Dew
Orographic precipitation	**Windward slopes**	Radiant energy
Relative humidity	**Hygrometer**	Wind vane
Cyclonic precipitation	**Frontal precipitation**	Psychrometer
Rain gauge	**Rainfall depth**	Windward slopes

7.5 Complete missing titles

h) Complete missing titles by using the following words and phrases **(Dew point, Storage, Speed, Humidity, Temperature, Runoff, Actinometer, Water, Science, Wind)** (B.Sc., DU, 2011)

1) Hydrology is derived from the Greek words: hydro (meaning **water**) and logos (meaning dealing with **science**).
2) When rainfall is more than infiltration, evaporation and evapotranspiration, ponds gather in low-lying areas representing Depression **storage**.
3) The water cycle consists of precipitation, evaporation, evapotranspiration and **runoff.**
4) Earth's rotation affects movement of **wind** and rotation of seasons.
5) Relative **humidity** is the percentage of actual vapor pressure to saturation vapor pressure.
6) **Dew point** denotes the temperature at which space becomes saturated when air is cooled under constant pressure & with constant water vapor pressure.
7) Shading effect of trees tends to keep daily maximum **temperature** somewhat lower.
8) **Actinometer** and Radiometer are general names for instruments used to measure intensity of radiant energy..
9) **Speed** would vary with the pressure gradient.

7.6 Match the words or phrases

Adiabatic	**Snow**	**Orographic**	**Precipitation**	**Convective**
Rain gauge	**Cyclone**	**Dew**	**Winds**	**Baric**

i) Match the words or phrases above with the definitions below. (B.Sc., DU, 2011)

1. Are mainly the result of horizontal differences in pressure.. (Winds)
2. Baric wind law is also known as Buys-Ballot's law. (Baric)
3. In this type of cooling heat is not added from outside sources. (Adiabatic)
4. It forms when cloud droplets (or ice particles) in clouds grow and combine to become so large that the updrafts in the clouds can no longer support them, and they fall to the ground. (Precipitation)
5. Represents frozen water pouring from clouds in small pieces. (Snow)
6. Denotes water vapor that condenses in the cold layers of the atmosphere during the night and falls to the ground in small droplets. (Dew)
7. In this type of precipitation most rain is deposited on the windward slopes. Other parts are located under the rain shadow and remain dry. (Orographic)
8. This type of precipitation results from lifting of air converging into a low pressure area. (Cyclone)
9. This type of precipitation is local, and its intensity varies from light rain showers to dangerous and destructive thunderstorms. (Convective)
10. It is a hydrological instrument used in measurements to calculate rainfall for the region. (Rain gauge)

7.7 مسائل اختبارية عامة بالعربية

العناصر الهيدرولوجية

1) اكتب بإيجاز عن أهم العوامل المؤثرة على المناخ. (بكالريوس، جامعة السودان للعلوم و التكنولوجيا، 2001).

2) كتلة من الهواء درجة حرارتها 22°م ورطوبتها النسبية 81 %. جد: ضغط البخار المتشبع، وضغط البخار الحقيقي، والعجز في التشبع، ونقطة الندى. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الحل

ب) 1- المعطيات: T = 22°م، h = 81%

2- جد من الجداول قيمة ضغط البخار المتشبع لدرجة حرارة 22°م

قيمة ضغط البخار المتشبع e_S = 19.82 ملم زئبق

3- بتعويض المعطيات في $h = 100*e/e_S$ جد ضغط البخار الحقيقي:

$81 = 100\times e \div 19.82$

ضغط البخار الحقيقي e = 16.05 ملم زئبق.

4- جد العجز في التشبع كما يلي:

العجز في التشبع: $e_S - e = 19.82 - 16.05 = 3.77$ ملم زئبق.

5- جد نقطة الندى على أنها درجة الحرارة التي يتساوى عندها قيم كل من e_S و e.

وبما أن: e_S = 16.05 ملم زئبق فعليه يمكن إيجاد درجة الحرارة، ومن ثم يمكن إيجاد نقطة الندى من الجداول ولقيمة e_S = 16.05 ، نقطة الندى = 18.6°م

3) استخدم بياني معادلة بنمان nomogram لحل معادلته للتكهن بالنتح اليومي المتوقع من نباتات حقلية على خط عرض 40 درجة شمال في شهر أبريل تحت الظروف التالية: درجة حرارة الهواء الوسيطة 20 درجة مئوية، والرطوبة المتوسطة 70 %، وتغطية السماء 60 % سحب، والسرعة النسبية على ارتفاع مترين 2.5 متر/ث، ونسبة النتح المتوقع للبخر المتوقع 0.7. ما الفرق في النتيجة على خط عرض 40 درجة جنوب؟ (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الحل

ج) المعطيات: تغطية السماء = 0.6 سحب، t = 20 °م، h = 0.7، u_2 = 2.5 م/ث، $n \div D = 1 - 0.6 = 0.4$، h = 0.7

- من النوموجراف لدرجة حرارة t = 20 °م وقيمة $n \div D = 0.4$ أوجد E_1 = -2.3 ملم/يوم
- ولدرجة حرارة t = 20 °م ومن الجداول لخط عرض 40° شمال وفي أبريل، أوجد معامل اقنوت: R_A = 847 جم كالوري/ سم لتر/يوم

ولقيم $n \div D = 0.4$ يمكن إيجاد E_2 = 3.7 ملم/يوم

- لدرجة حرارة t = 20 °م، $n \div D = 0.4$، h = 0.7 أوجد: E_3 = 1.3 ملم/يوم
- لدرجة حرارة t = 20 °م، ورطوبة h = 0.7، وسرعة u_2 = 2.5 م/ث جد: E_4 = 1.1 ملم/يوم
- جد E_o من المعادلة:

$$E_o = E_1 + E_2 + E_3 + E_4 = -2.3 + 3.7 + 1.3 + 1.1 = 3.6 \text{ mm/day}$$

$$E_{trans} = 0.7\, E_o = 0.7 \times 3.6 = 2.5 \text{ mm/day.}$$

- كرر لخط عرض 40 درجة جنوب

السؤال الأول

4) عرف ووضح: نقطة الندى، وقانون بالوت، والتساقط الإعصاري، وخريطة تساوي المطر. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

5) كتلة من الهواء درجة حرارتها 24.5°م ورطوبتها النسبية 58 %. جد: ضغط البخار المتشبع، وضغط البخار الحقيقي، والعجز في التشبع، ونقطة الندى. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

6) استخدم بياني معادلة بنمان nomogram لحل معادلته للتكهن بالنتح اليومي المتوقع من نباتات حقلية على خط عرض 60 درجة شمال في شهري مارس ويونيو ، لنسبة النتح المتوقع للبخر المتوقع 65 بالمائة للبخر المتوقع، تحت الظروف التالية: (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

	مارس	يونيو
درجة حرارة الهواء الوسيطة (درجة مئوية)	5.5	15
الرطوبة النسبية المتوسطة (%)	79	77
تغطية السماء (% سحب)	45	55
السرعة النسبية للرياح (متر/ث)	2.5	3

7) اكتب بإيجاز عن طرق قياس التساقط في منطقة ما. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

8) جد التساقط المتوسط في حوض ساكب طبقاً للمعلومات والبيانات الموضحة في الجدول التالي باستخدام طريقتي المتوسط الحسابي وطريقة ثايسن. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

المحطة	مقياس المطر (سم)	المساحة (%)
1	62	8
2	74	11
3	87	20
4	112	18
5	118	33
6	107	10

الحل

1- المعطيات: تقديرات الأمطار في المحطات.

2- جد متوسط الأمطار الهاطلة بالمنطقة باستخدام طريقة المتوسط الحسابي من المعادلة: $P_{av} =$ □(P_i/n)

$P_{av} = (62 + 74 + 87 + 121 + 181 + 107) \div 6 = 93.3$ سم.

3- جد متوسط الأمطار الهاطلة بالمنطقة باستخدام طريقة ثايسن:

$P_{mean}=(A_1/A)P_1+(A_2/A)P_2+..+ (A_n/A)P_n$

التساقط المتوسط = $(8\times62 + 11\times74 + 20\times87 + 18\times112 + 33\times118 + 10\times107) \div 100 =$ 100.3 سم.

9) جد شدة المطر المتوسط عبر مساحة 6 كيلو متر مربع خلال زوبعة مدتها ساعة لتردد مرة كل عشر سنوات (بافتراض مطر النقطة 30 ملم، وجاما عكسية 5.6). (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الحل

المعطيات: A = 6 كيلو متر مربع، t = 60 دقيقة، t* = 5.6، P = 30 ملم.

أوجد نسبة سمك المطر المتوسط من المعادلة:

$$\bar{P} = P\left(1-\frac{0.3\sqrt{A}}{t^*}\right) = 30\left(1-\frac{0.3\sqrt{6}}{5.6}\right) = 26\,\text{mm}$$

$\bar{P}$ = 26 ملم في ساعة واحدة.

10) قيمة دليل التساقط API لمحطة ما بلغ 42 ملم في الأول من أغسطس، وسقط مقدار 46 ملم من المطر في الخامس من أغسطس، كما هطلت28 ملم من الأمطار في السابع منه و34 ملم في اليوم الثامن من أغسطس. جد قيمة دليل التساقط API ليوم 12 أغسطس علماً بأن k تساوي 0.92. احسب مقدار الدليل بافتراض عدم هطول أمطار في نفس الفترة. ارسم منحنى تغير الدليل مع الزمن. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الحل

1. بما أن $I_t = I_0 k^t$ وبفرض t = 1 ينتج: $I_t = I_0 k$. الذي يعني أنه لأي يوم تساوي قيمة الدليل تلك القيمة في اليوم السابق مضروبة في معامل k. ومن ثم إذا هطلت أمطار في أي يوم تضاف قيمة هذه الأمطار للدليل.
2. من البيانات المعطاة:

في اليوم الأول من أغسطس $I_1 = 42$ ملم

- مباشرة في اليوم الخامس من أغسطس $I_5 = 42(0.92)^4 = 30.1$ mm
- في اليوم الخامس من أغسطس ينبغي إضافة المطر الذي هطل $I_5 = 30.1 + 46 = 76.1$ ملم
- مباشرة في اليوم السابع من أغسطس $I_7 = 76.1(0.92)^2 = 64.4$ mm
- في اليوم السابع من أغسطس ينبغي إضافة المطر الذي هطل $I_7 = 64.4 + 28 = 92.4$ ملم
- مباشرة في اليوم الثامن من أغسطس $I_8 = 92.4(0.92)^1 = 85$ mm
- في اليوم الثامن من أغسطس ينبغي إضافة المطر الذي هطل $I_8 = 85 + 34 = 119$ ملم
- في اليوم الثاني عشر من أغسطس $I_{12} = 119(0.92)^4 = 85.3$ mm

3. في حالة عدم هطول أمطار: $I_{12} = 42(0.92)^{11} = 1.7$ mm
4. رسم المنحنى

11) جد مقدار دليل فاى للمنطقة الجابية لإحداث انسياب سطحي مقداره 19.5 ملم، إذا علم أن قيمة المطر الكلي لموقع ما تساوي 44 ملم حسب التقسيم المبين في الجدول التالي: (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الزمن (ساعة)	شدة الأمطار (ملم/ساعة)
صفر	صفر
1	4
2	21
3	9
4	6
5	4

الحل

1- المعطيات: تغير شدة الأمطار مع الزمن، ومعدل الانسياب سطحي = 19.5 ملم.
2- أرسم شدة الأمطار مع الزمن كما مبين على شكل "حل المثال".
3- أوجد دليل فاى باستخدام المعادلة:

معدل الأمطار الأعلى من فاى = معدل الأمطار الأدنى من فاى = معدل الانسياب السطحي

$$(\phi - 6)1 + (\phi - 9)1 + (\phi - 21)1 = 19.5$$

ومن ثم يمكن إيجاد دليل فاى ليساوي: $\phi = 5$ ملم/ساعة.

12) اكتب بإيجاز عن طرق قياس التساقط في منطقة ما. أي طريقة أفضل؟ ولماذا؟ (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

13) جد التساقط المتوسط في حوض ساكب طبقاً للمعلومات والبيانات الموضحة في الجدول التالي باستخدام طريقة خطوط المطر المتساوي. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

خطوط المطر المتساوي (بوصة)	المساحة الكلية المحصورة بين حدود الحوض (هكتار)	المطر المتوسط المقدر بين الخطوط (بوصة)
> 6	40	6.5
> 5	110	5.5
> 4	236	4.5
> 3	430	3.5
> 2	772	2.5
> 1	990	1.5
< 1	1010	0.9

14) قيمة دليل التساقط API لمحطة ما بلغ 55 ملم في الأول من أغسطس، وسقط مقدار 57 ملم من المطر في السادس من أغسطس، كما هطلت31 ملم من الأمطار في الثامن منه و20 ملم في اليوم التاسع من أغسطس. جد قيمة دليل التساقط API ليوم 15 أغسطس علماً بأن k تساوي 0.92. احسب مقدار الدليل بافتراض عدم هطول أمطار في نفس الفترة. ارسم منحنى تغير الدليل مع الزمن. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

المياه الجوفية

1) جد معادلة الدفق المستقر في خزان جوفي محجوز (دفق قطري) من المبادئ الأولية علماً بأن الدفق Q، وسرعة الإنسياب □ ، ومعامل نفاذية الحوض k، والاتجاه القطري r، وانخفاض المنسوب S، وعمق الخزان H، والمنقولية T. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

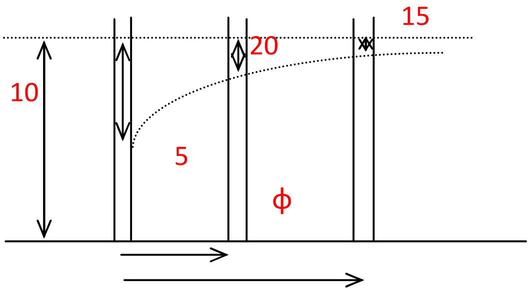
2) حفرت بئر إلى القاعدة المسيكة في مركز جزيرة دائرية قطرها 1.5 كيلومتر في بحيرة كبيرة. تتغلغل البئر كلية في خزان الحجر الرملي الذي يبلغ سمكه 18 متراً والذي تحت طبقة طين مسيكة. نفاذية الحجر الرملي تساوي 15 متر في اليوم. جد الدفق المستقر إذا كان انخفاض المنسوب للسطح البيزومتري لا يجب أن يتجاوز 2 متر في البئر التي قطرها 0.3 متر. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

3) ما أهم الفروقات بين الانسياب عبر خزان جوفي مجحوز وآخر غير محجوز؟(بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

4) اكتب بإيجاز عن أنواع الآبار. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

5) بئر جاذبية قطرها 50 سم. عمق الماء في البئر 30 متر قبل بداية الضخ. وعند إجراء الضخ بمعدل 2100 لتر في الدقيقة، انخفض المنسوب في بئر تبعد عنها 10 متر بمقدار 3 متر؛ وبلغ في بئر أخرى تبعد 20 متراً انخفض عنها حوالي 1.5 متر. جد: نصف قطر انخفاض المنسوب الصفري zero draw down ، ومعامل النفاذية، وانخفاض المنسوب في البئر. ارسم مخروط انخفاض المنسوب من جراء الضخ لهذه البئر. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الحل



ج) استخدم المعادلة

$$Q_o = \frac{\pi k\left(H^2 - h_0^2\right)}{Ln\frac{R}{r_o}}$$

0 – 3 = 27 m3r = 10 m, h =

0 - 1.5 = 28.5 m3r = 20 m, h =

$$\therefore \left[\frac{\pi k\left(H^2 - h_0^2\right)}{Ln\frac{R}{r_o}}\right]_{ist\ well} = \left[\frac{\pi k\left(H^2 - h_0^2\right)}{Ln\frac{R}{r_o}}\right]_{2nd\ well}$$

$$\left[\frac{\left(30^2 - 27^2\right)}{Ln\frac{R}{10}}\right] = \left[\frac{\left(30^2 - 28.5^2\right)}{Ln\frac{R}{20}}\right]_1$$

ومنها: R = 41.5 متر

جد معامل النفاذية من المعادلة لبيانات البئر التي تبعد 10 متر H = 30م، h = 27 م، r = 10 م، R = 41.5 م، Q = 2100 لتر/دقيقة = 2.1 م^3/دقيقة = 3024 م^3/يوم

$$k = \frac{QLn\frac{R}{r_o}}{\pi\left(H^2 - h_0^2\right)} = \frac{3024Ln\frac{41.5}{10}}{\pi\left(30^2 - 27^2\right)} = 8m/d$$

لإيجاد عمق الماء في البئر استخدم المعادلة:

$$h_0^2 = H^2 \quad - \quad \frac{Q}{\pi k}Ln\frac{R}{r} = 40^2 \quad - \quad \frac{3024}{\pi x8}Ln\frac{41.5}{0.25} = 615$$

ومنها: h = 24.8 متر

الانخفاض في المنسوب = 30 – 24.8 = 5.2 متر

6) ما أهم العوامل المؤثرة على إنتاجية البئر الجوفي؟n(بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

7) المستوى الساكن لسطح الماء في خزان جوفي غير محجوز 33.5 متر فوق الطبقة المسيكة تحته. أجرى الضخ بمعدل 20 لتر في الثانية في بئر قطرها 150 ملم تتغلغل عبر كل عمق الخزان. وبعد بضع أسابيع من الضخ في آبار مراقبة على بعد 20 متر و50 متر منها انخفض المنسوب بمقدار 3.55 متر و2.27 متراً على الترتيب وتزيد الانخفاضات تدريجياً وببطء. بافتراض ظروف توازن جد: معامل النفاذية الهيدروليكية، وانخفاض المنسوب مباشرة خارج البئر التي يضخ منها الماء. ارسم مخروط انخفاض المنسوب من جراء الضخ لهذه البئر. ما مقدار انتاجية بئر قطرها 300 ملم يمكنها تحقيق نفس الانخفاض في المنسوب مباشرة خارجها وعلى بعد 50 متر من بئر المراقبة. وما مقدار انخفاض المنسوب في بئر المراقبة المجاورة؟(بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

الانسياب السطحي

1) ما فوائد منحنى الانسياب؟ وما أهم استخداماته؟(بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

2) صمم مستودع مائي لتجميع كميات المياه الهاطلة في الحوض الساكب المجاور له لتنظيم الإمداد بمتوسط دفق منتظم يعادل 284 متراً مكعباً في الدقيقة. ويبين الجدول التالي سجلات دفق المجرى

المائي الشهرية مقدرة بالمليون متر المكعب. جد مقدار الخزن اللازم لمواكبة الاستهلاك المنتظم بافتراض عدم فقدان للماء. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الشهر	حجم الماء (مليون متر مكعب)	الشهر	حجم الماء (مليون متر مكعب)
يناير	7.4	فبراير	49.4
مارس	31.1	إبريل	34.6
مايو	29.6	يونيو	8.6
يوليو	2.5	أغسطس	1.2
سبتمبر	18.5	أكتوبر	58
نوفمبر	76.5	ديسمبر	82.7

الحل

1- المعطيات: الاستهلاك المنتظم 284 م^3/دقيقة، وبيانات دفق الماء الشهرية.

2- جد الدفق التراكمي الكلي كما موضح في الجدول التالي:

الشهر	حجم الماء (مليون متر مكعب)	الدفق التراكمي (مليون متر مكعب)
يناير	7.4	7.4
فبراير	49.4	56.8
مارس	31.1	87.9
إبريل	34.6	122.5
مايو	29.6	152.1
يونيو	8.6	160.7
يوليو	2.5	163.2
أغسطس	1.2	175.2
سبتمبر	18.5	193.7
أكتوبر	58	251.7
نوفمبر	76.5	328.2
ديسمبر	82.7	410.9

3- ارسم منحنى دفق الكتلة (مخطط ربل) للبيانات برسم قيم الدفق التراكمي كمتغير بالنسبة للزمن كما مبين على رسم حل المثال.

4- جد قيمة معدل الاستهلاك المنتظم السنوي (لشهر ديسمبر) =

284 (م^3/ دقيقة) × 60 (دقيقة/ ساعة) × 24 (ساعة/ يوم) × 365 (يوم/ سنة) = ٤٤٤٤×10^6 م^3/ سنة.

5- ارسم خط السحب المنتظم من نقطة الأصل إلى النقطة (أ) على منحنى دفق الكتلة.

6- ارسم خطاً موازياً لخط السحب من النقطة التي يكون فيها الخزان ممتلئاً (ب)، ثم جد قيمة أقل تخزين مطلوب للمستودع لمواكبة الاستهلاك = ٤٤٤×10^6 م^3.

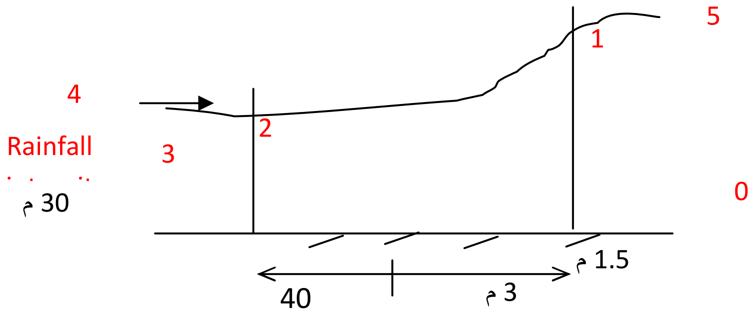
(3) كيف يُقدّر الانسياب السطحي لمجرى مائي؟(بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

(4) قياس جريان نهر خلال الفيضان أبان أن Q_a = 2700 متر مكعب في الثانية. وأثناء القياس الذي استمر لساعتين زاد ارتفاع المقياس من 40.48 متر إلى 40.36 متر. قراءات المستوى على سطح الماء على مسافة 390 متر و310 متر أعلى اتجاه التيار وأدناه من موقع المراقبة اختلفت بحوالي 100 مليمتر. عرض النهر 400 متر، ومتوسط عمقه 3.5 متر أثناء لحظة القياسات. جد إحداثيات النقطة التي ينبغي وضعها للقياسات في منحنى المعايرة. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الحل

المعطيات: العرض = 400م، العمق = 3.5م، dt = 2 ساعة

= 0.12 m360.4 – 480.4dh =



المساحة = العرض×العمق = 3.5×400 = 1400 م^2
السرعة المتوسطة للماء $\bar{v}$ = Qa ÷ A = 2700 ÷ (3.5×400) = 1.93 م/ث

$$\frac{dh}{dt} = \frac{0.12m}{2x3600s} = 1.67x10^{-5} m/s$$

جد سرعة موجة الفيض من المعادلة: $U = 1.3\frac{Q_a}{A} = 1.3x1.93 = 2.51 \quad m/s$

الميل = 0.1 ÷ 700 = 1.43×10 $^{-4}$ م/م

جد الجريان المعدل من المعادلة:

$$Q_{orrected} = \frac{Q_a}{\sqrt{\left(1+\frac{A}{US}\frac{dh}{dt}\right)}} = \frac{2700}{\sqrt{\left(1+\frac{1.67x10^{-5}}{2.53x1.43x10^{-4}}\right)}} = 2639 \quad m^3/s$$

جد الارتفاع المتوسط للمقياس = (40.48 + 40.36) ÷ 2 = 40.42 متر
ومن ثم الإحداثيات على منحنى المعايرة (40.42، 2639)

5) يبلغ معدل الانسياب في مجرى مائي يقوم بتصريف حوض ساكب 3950 م^3/دقيقة بعد مضـى عشرة أيام غير مطيرة، كما ويبلغ معدل الانسياب فيه 1190 م^3/دقيقة بعد مضـى شهر من غير هطلان أمطار. ارسم المنحنى المائي الزمني للانسياب القاعدي؛ وجد مقدار معدل الانسياب بعد مضـى فترة شهرين وفترة خمسة أشهر بالمجرى المائي. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الحل

1- المعطيات: قيم معدل الانسياب Qt و Qa بعد مضـى ثمانية أيام وشـهر، Q10 = 3950، Q30 = 1190 م^3/دقيقة

2- جد معادلة هيدروجراف الانسياب القاعدي باستخدام المعادلة: Qt = Qo*e-□ t

عوض القيم المعطاة في المعادلة كما موضح أدناه في المعادلتين 1 و2.

Qo= 3950 ×e$^{-10×□}$ (1)

1190 = Qo ×e$^{-30×□}$ (2)

بقسمة المعادلتين 1 و2 يمكن إيجاد قيمة معامل الحوض □ ليساوى: a = 0.06

3- عوض في إحدى المعادلتين 1 أو 2 لإيجاد قيمة التصرف الابتدائي Qo كالآتي:

Qo = (3950÷60)÷e$^{-10×0.06}$ = 120 م3/ث

4- تصبح معادلة هيدروجراف الانسياب القاعدي : Qt = 120*e-0.06*t

5- جد مقدار معدل الدفق بعد مضـى فترة ثلاثة أشهر بـالمجرى المـائي بـالتعويض فـي معادلـة هيدروجراف الانسياب القاعدي التي تم الحصول عليها في الخطوة 4 أعلاه: $Q_t = 120*e^{-0.06*t}$

$Q_{90} = 120 \div e^{-0.06\times 90} = 0.54$ م^3/ث

6- بتكرار الخطوة 5 أعلاه يمكن إيجاد معدل الدفق بعد مضى فترة خمسة أشهر بالمجرى المائي:
وعليه $Q_{150} = 120 \div e^{-0.06\times 150} = 0.015$ م^3/ث.

6) احسب هيدروجراف الوحدة لساعة لمنطقة معينة وارسمه علماً بأن مساحة تصريفها 70 كيلومتر مربع. والجريان من قمة واحدة لتساقط 20 ملم كما ممثل في الجدول التالي: (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2001).

الزمن (ساعة)	الجريان المقاس (م^3/ث)
0	0
1	3.8
2	11.2
3	12.3
4	11.1
5	8.2
6	5.2
7	3.6
8	3.2
9	2.8
10	2.6
11	2.3
12	2.2
13	2.1
14	2.0
15	1.9
16	1.8
17	1.7
18	1.6
19	1.5
20	1.4
21	0

الحل

د) النهر جاف مباشرة قبل وبعد الزوبعة المطرية، ومن ثم لا يوجد جريان أساسي ليفصل.
متوسط الجريان المقياس Q_{av} من البيانات المعطاة:

$$Q_{aV} = \frac{82.5}{21} = 3.93\ m^3/s$$

الجريان الكلي = متوسط الجريان المقاس × الزمن

$$Q_T = Q_{av} \cdot t = 3.93 \frac{m^3}{s} \times 21^h \times 3600 \frac{s}{h} = 297000\,m^3$$

سمك الجريان = الجريان الكلي ÷ المساحة

$$\text{runoff depth} = \frac{297000}{70 \times 10^6} = 4.24 \times 10^{-3}\,m = 4.24\,mm$$

ومن ثم يقسم الجريان المقاس في الجدول بالمقدار 4.24 للحصول على هيدروجراف الوحدة.

الدفق المتوسط: $Q_{av} = 82.5 \div 21 = 3.93$ م^3/ث

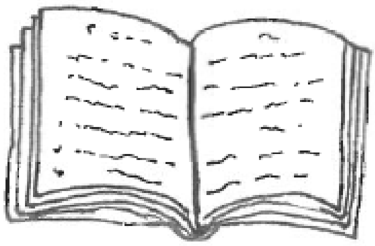
هيدروجراف الوحدة (م^3/ث)	الدفق المقاس (م^3/ث)	الزمن (ساعة)
0	0	0
0.9	3.8	1
2.64	11.2	2
2.9	12.3	3
2.62	11.1	4
1.93	8.2	5
1.23	5.2	6
0.85	3.6	7
0.75	3.2	8
0.66	2.8	9
0.61	2.6	10
0.54	2.3	11
0.52	2.2	12
0.5	2.1	13
0.47	2.0	14
0.45	1.9	15
0.42	1.8	16
0.4	1.7	17
0.4	1.6	18
0.35	1.5	19
0.33	1.4	20
0	0	21
	$\sum Q = 82.5$	

7) ما المقصود بهيدروجراف الوحدة. ووضح الافتراضات المدرجة في نظرية الهيدروجراف. (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

8) احسب هيدروجراف الوحدة لساعة لمنطقة معينة وارسمه علماً بأن المطر الساقط 35 ملم في مساحة تصريف مساحتها 78.2 كيلومتر مربع عبر فترة ساعة واحدة بدأت الساعة 01:00. والجدول التالي يبين الجريان المقاس عبر المساحة في وحدة الزمن: (بكالريوس، جامعة السودان للعلوم والتكنولوجيا، 2002).

الزمن (ساعة)	الجريان المقاس (م^3/ث)	الزمن (ساعة)	الجريان المقاس (م^3/ث)
0	0	10	2.83
1	1	11	2.38
2	1.2	12	2.02
3	2.97	13	1.76
4	24.1	14	1.64
5	51.5	15	1.47
6	32.3	16	1.39
7	11.2	17	1.27
8	5.95	18	0
9	3.77		

References and bibliography for further reading



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Useful Formulae

1) $e = P - P'$

2) $e_W - e = \gamma (t - t_W)$

3) $P_x = \dfrac{\dfrac{N_x P_a}{N_a} + \dfrac{N_x P_b}{N_b} + \dfrac{N_x P_c}{N_c}}{3}$ $P_{mean} = \dfrac{A_1}{A} P_1 + \dfrac{A_2}{A} P_2 + ... + \dfrac{A_n}{A} P_n = \left(\sum_{i=1}^{n} A_i P_i \right) \div \left(\sum_{i=1}^{n} A_i \right)$

4) $P_{av} = \sum_{i=1}^{n} \dfrac{P_i}{n}$

5) $P_{mean} = \dfrac{\sum_{i=1}^{n} A_i P_i}{\sum_{i=1}^{n} A_i}$

6) $i = \dfrac{a}{t+b}$

7) $i = \dfrac{c}{t^n}$

8) $i = \dfrac{60P}{t}$

9) $P = \left(\dfrac{1.214 \times 10^5}{600} \times Nt \right)^{0.282} - 2.54$

10) $\dfrac{\overline{P}}{P} = 1 - \dfrac{0.3\sqrt{A}}{t^*}$

11) $i = \left(\dfrac{60}{t} \right) \times \left[(202.3Nt)^{0.282} - 2.54 \right]$

12) $EV = b(e_S - e)$

13) $EV = f(u).\ (e_s - e)$

14) $E_T = \dfrac{\Delta H + \gamma E_a}{\Delta + \gamma}$

15) $E_T = E_1\left(t, \dfrac{n}{D}\right) + E_2\left(t, R_A, \dfrac{n}{D}\right) + E_3\left(t, \dfrac{n}{D}, h\right) + E_4\left(t, u_2, h\right)$

16) $f = f_c + (f_o - f_c)e^{-kt}$

17) $F = \int_0^t f dt = f_c t + \left(\dfrac{(f_o - f_c)}{k_f} \right)(1 - e^{k_f t})$

18) $F_c = \dfrac{(f_o - f_c)}{k_f}$

19) $I_t = I_O * k^t$

20) $v = k*i$

21) $\overline{v} = \dfrac{v}{n_e}$

22) $v = -k \dfrac{d\phi}{dx}$

23) $q = -kH. \dfrac{d\phi}{dx}$

24) $\phi = -\dfrac{v.x}{k}$

25) $q = -kh\frac{dh}{dx}$

26) $q = \frac{k\left(h_o^2 - h^2\right)}{2x}$

27) $h^2 = -\frac{Nx^2}{k} + ax + b$

28) $S_1 - S_2 = \frac{Q_o}{2\pi kH} Ln\left(\frac{r_2}{r_1}\right)$

29) $k = \frac{Q}{2\pi H\left(S_1 - S_2\right)} Ln\left(\frac{r_2}{r_1}\right)$

30) $T = kH = \frac{Q}{2\pi\left(S_1 - S_2\right)} Ln\frac{r_2}{r_1}$

31) $S = \frac{Q_o}{2\pi kH} \ln\frac{R_o}{r} = \frac{Q_o}{2\pi T} \ln\frac{R_o}{r}$

32) $Q_o = \frac{\pi k\left(H^2 - h_o^2\right)}{Ln\frac{R}{r_o}}$

33) $H^2 - h^2 = \frac{Q_o}{\pi k} Ln\frac{R}{r} - \frac{N}{2k}\left(R^2 - r^2\right)$

34) $Q = \pi R^2 N$

35) Q = 27.78 C I A

36) Q = 2.78 C I A

37) $i = \frac{c\,T^m}{\left(t+d\right)^n}$

38) $\frac{Q_a}{Q} = \sqrt{\left(1 + \frac{1}{US}\frac{dh}{dt}\right)}$

39) $U = 1.3\frac{Q_a}{A}$

40) $\frac{Q_a}{Q} = \sqrt{\left(1 + \frac{A}{1.3Q_a S}\frac{dh}{dt}\right)}$

41) $Q = k\,(h - a)^x$

42) $Q = AC\sqrt{r_H \cdot S}$

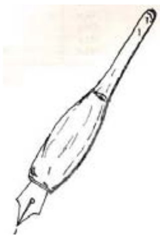
43) $I - D = \frac{\Delta S}{\Delta t}$

44) $N = b.A^{0.2}$

45) $0.5\,(I_1 + I_2)\Delta t - 0.5\,(D_1 + D_2)\Delta t = S_2 - S_1$

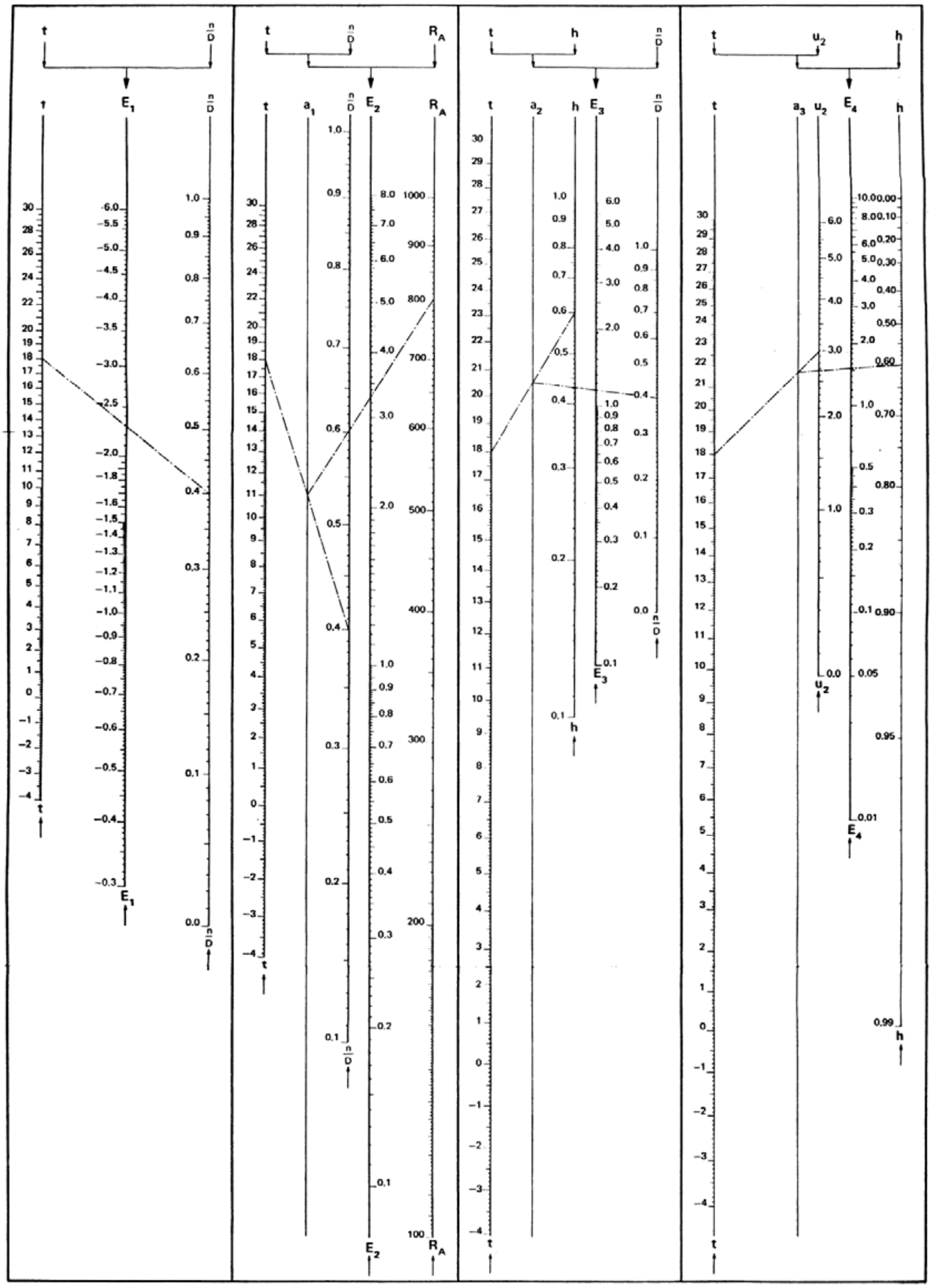
46) S = K[XI + (1 - X)D] 47)

Appendices



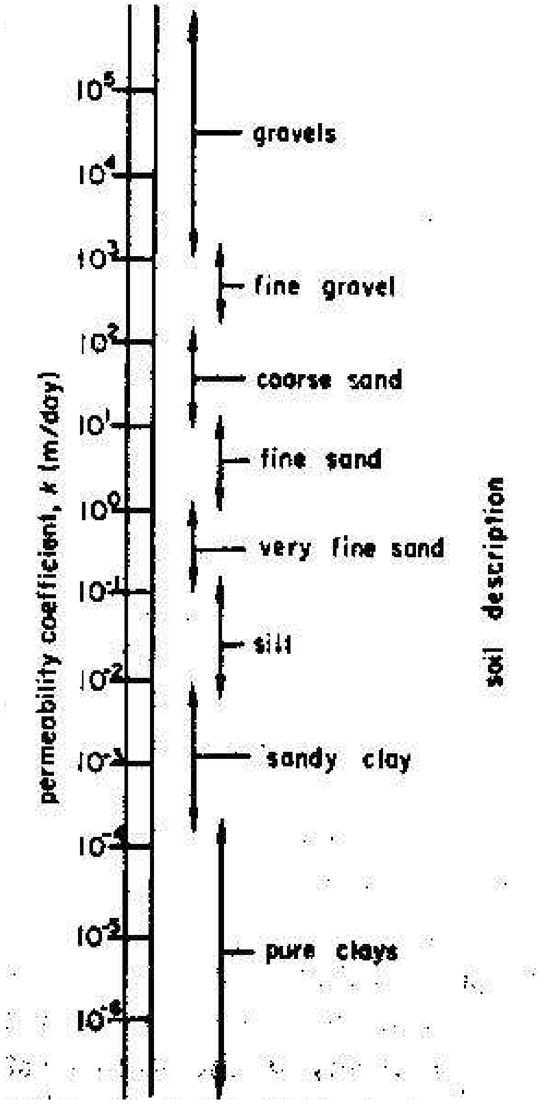
NOMOGRAM FOR DETERMINING EVAPORATION E_0 FROM A FREE WATER SURFACE ACCORDING TO THE FORMULA OF PENMAN

$$E_0 = \frac{\Delta H + \gamma E_a}{\Delta + \gamma} = E_1\left(t, \frac{n}{D}\right) + E_2\left(t, R_A, \frac{n}{D}\right) + E_3\left(t, \frac{n}{D}, h\right) + E_4(t, u_2, h)$$



Appendix (B) Agot's values of short-wave radiation flux R_A at the outer limit of the atmosphere in g cal/cm^2/day as a function of the month of the year & latitude.

Latitude (Degrees)	Jan	Feb.	Mar	April	May	June	July	august	Sept.	Oct.	Nov.	Dec.	Year
N 90	0	0	55	518	903	1077	944	605	136	0	0	0	3540
80	0	3	143	518	875	1060	930	600	219	17	0	0	3660
60	86	234	424	687	866	983	892	714	494	258	113	55	4850
40	38	538	663	847	930	1001	941	843	719	528	397	318	6750
20	631	795	821	914	912	947	912	887	856	740	666	599	8070
Equator	844	963	878	876	803	803	792	820	891	866	873	829	8540
20	970	1020	832	737	608	580	588	680	820	892	986	978	8070
40	998	963	686	515	358	308	333	453	648	817	994	1033	670
60	947	802	459	240	95	50	77	187	403	648	920	1013	4850
80	981	649	181	9	0	0	0	0	113	459	917	1094	3660
S 90	995	656	92	0	0	0	0	0	30	447	932	1110	3540



Appendix (C) Soil descriptions with permeability coefficient.

Appendix (D) Saturation vapour pressure as a function of temperature t

(Negative values of t refer to conditions over ice; 1 mm Hg = 1.33 mbar)

t (°C)	e_s 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
−10	2.15									
−9	2.32	2.30	2.29	2.27	2.26	2.24	2.22	2.21	2.19	2.17
−8	2.51	2.49	2.47	2.45	2.43	2.41	2.40	2.38	2.36	2.34
−7	2.71	2.69	2.67	2.65	2.63	2.61	2.59	2.57	2.55	2.53
−6	2.93	2.91	2.89	2.86	2.84	2.82	2.80	2.77	2.75	2.73
−5	3.16	3.14	3.11	3.09	3.06	3.04	3.01	2.99	2.97	2.95
−4	3.41	3.39	3.37	3.34	3.32	3.29	3.27	3.24	3.22	3.18
−3	3.67	3.64	3.62	3.59	3.57	3.54	3.52	3.49	3.46	3.44
−2	3.97	3.94	3.91	3.88	3.85	3.82	3.79	3.76	3.73	3.70
−1	4.26	4.23	4.20	4.17	4.14	4.11	4.08	4.05	4.03	4.00
−0	4.58	4.55	4.52	4.49	4.46	4.43	4.40	4.36	4.33	4.29
0	4.58	4.62	4.65	4.69	4.71	4.75	4.78	4.82	4.86	4.89
1	4.92	4.96	5.00	5.03	5.07	5.11	5.14	5.18	5.21	5.25
2	5.29	5.33	5.37	5.40	5.44	5.48	5.53	5.57	5.60	5.64
3	5.68	5.72	5.76	5.80	5.84	5.89	5.93	5.97	6.01	6.06
4	6.10	6.14	6.18	6.23	6.27	6.31	6.36	6.40	6.45	6.49
5	6.54	6.58	6.54	6.68	6.72	6.77	6.82	6.86	6.91	6.96
6	7.01	7.06	7.11	7.16	7.20	7.25	7.31	7.36	7.41	7.46
7	7.51	7.56	7.61	7.67	7.72	7.77	7.82	7.88	7.93	7.98
8	8.04	8.10	8.15	8.21	8.26	8.32	8.37	8.43	8.48	8.54
9	8.61	8.67	8.73	8.78	8.84	8.90	8.96	9.02	9.08	9.14
10	9.20	9.26	9.33	9.39	9.46	9.52	9.58	9.65	9.71	9.77
11	9.84	9.90	9.97	10.03	10.10	10.17	10.24	10.31	10.38	10.45
12	10.52	10.58	10.66	10.72	10.79	10.86	10.93	11.00	11.08	11.15
13	11.23	11.30	11.38	11.75	11.53	11.60	11.68	11.76	11.83	11.91
14	11.98	12.06	12.14	12.22	12.96	12.38	12.46	12.54	12.62	12.70
15	12.78	12.86	12.95	13.03	13.11	13.20	13.28	13.37	13.45	13.54
16	13.63	13.71	13.80	13.90	13.99	14.08	14.17	14.26	14.35	14.44
17	14.53	14.62	14.71	14.80	14.90	14.99	15.09	15.17	15.27	15.38
18	15.46	15.56	15.66	15.76	15.96	15.96	16.06	16.16	16.26	16.36
19	16.46	16.57	16.68	16.79	16.90	17.00	17.10	17.21	17.32	17.43
20	17.53	17.64	17.75	17.86	17.97	18.08	18.20	18.31	18.43	18.54
21	18.65	18.77	18.88	19.00	19.11	19.23	19.35	19.46	19.58	19.70
22	19.82	19.94	20.06	20.19	20.31	20.43	20.58	20.69	20.80	20.93
23	21.05	21.19	21.32	21.45	21.58	21.71	21.84	21.97	22.10	22.23
24	22.27	22.50	22.63	22.76	22.91	23.05	23.19	23.31	23.45	23.60
25	23.75	23.90	24.03	24.20	24.35	24.49	24.64	24.79	24.94	25.08
26	25.31	25.45	25.60	25.74	25.89	26.03	26.18	26.32	26.46	26.60
27	26.74	26.90	27.05	27.21	27.37	27.53	27.69	27.85	28.00	28.16
28	28.32	28.49	28.66	28.83	29.00	29.17	29.34	29.51	29.68	29.85
29	30.03	30.20	30.38	30.56	30.74	30.92	31.10	31.28	31.46	31.64
30	31.82	32.00	32.19	32.38	32.57	32.76	32.95	33.14	33.33	33.52

Appendix (E)
Some Physical Properties of Water at Various Temperatures.

Temperature, ^{o} C	Density, kg/m^3	Dynamic viscosity $\mu x10^3$ Ns/m^2	Kinematic viscosity $\nu x10^6$ m^2/s
0	999.8	1.793	1.792
5	1000	1.519	1.519
10	999.7	1.308	1.308
15	999.1	1.140	1.141
20	998.2	1.005	1.007
25	997.1	0.894	0.897
30	995.7	0.801	0.804
35	994.1	0.723	0.727
40	992.2	0.656	0.661
45	990.2	0.599	0.605
50	988.1	0.549	0.556
55	985.7	0.506	0.513
60	983.2	0.469	0.477
65	980.6	0.436	0.444
70	977.8	0.406	0.415
75	974.9	0.380	0.390
80	971.8	0.357	0.367
85	968.6	0.336	0.347
90	965.3	0.317	0.328
95	961.9	0.299	0.311
100	958.4	0.284	0.296

Appendix (F)
Conversion Table

Multiply	by	to obtain
	Area	
acre	43560	ft^2
acre	4047	m^2
cm^2	0.155	in^2
ft^2	0.0929	m^2
hecatre, ha	2.471	acre
in^2	6.452	cm^2
km^2	0.3861	$mile^2$
m^2	10.76	ft^2
mm^2	0.00155	in^2
	Concentration	
mg/l	8.345	lb/million USA gal
ppm	1	mg/L
	Density	
g/cm^3	1000	kg/m^3
g/cm^3	1	kg/L
g/cm^3	62.43	lb/ft^3
g/cm^3	10.022	lb/gal (Br.)
g/cm^3	8.345	lb/gal (USA)
kg/m^3	0.001	g/cm^3
kg/m^3	0.001	kg/L
kg/m^3	0.6242	lb/ft^3
	Flowrate	
ft^3/s	448.8	gal/min
ft^3/s	28.32	L/s
ft^3/s	0.6462	M gal/d
M gal/d	1.547	ft^3/s
gal/min	0.00223	ft^3/s
gal/min	0.0631	L/s
L/s	15.85	gal/min
m^3/hr	4.4	gal/min
m^3/s	35.31	ft^3/s
	Length	
ft	30.48	cm
in	2.54	cm
km	0.06214	mile
km	3280.8	ft
m	39.37	in
m	3.281	ft
m	1.094	yard
mile	5280	ft
mile	1.6093	km
mm	0.03937	in
	Mass	
g	$2.205*10^{-3}$	lb
lb	16	ounce
kg	2.205	lb
tonne, t	1.102	ton (2000 lb)
	Power	
Btu	252	cal
Btu	778	ft-lb

Btu	$3.93*10^{-4}$	HP-hr
Btu	$2.93*10^{-4}$	kW-hr
HP	0.7457	kW
	Pressure	
atm	760	mm Hg
atm	29.92	in Hg
atm	33.93	ft water
atm	10.33	m water
atm	$1.033*10^4$	kg/m^2
atm	$1.013*10^5$	N/m^2
in water	1.8665	mm Hg
in Hg	0.49116	lb/in^2
in Hg	25.4	mm Hg
k Pa	0.145	lb/in^2, psi
mm Hg	0.01934	lb/in^2
mm Hg	13.595	kg/m^2
lb/in^2	6895	N/m^2
lb/in^2	0.0703	kg/cm^2
	Temperature	
Fahrenheit, F	5*(F – 32)/9	Centigrade, C
Centigrade, C	(9C/5) + 32	F
C	C + 273.16	Kelvin, K
Rankine	F + 459.69	F
	Velocity	
ft/s	30.48	cm/s
ft/s	1.097	km/hr
ft/min	0.508	cm/s
cm/s	0.03281	ft/s
cm/s	0.6	m/min
m/s	3.281	ft/s
m/s	196.8	ft/min
	Viscosity	
centipoise	0.01	g/cm.s
centistoke	0.01	cm^2/s
	Volume	
ft^3	0.02832	m^3
ft^3	6.229	gal (Br.)
ft^3	7.481	gal (USA)
ft^3	28.316	L
gal	0.1337	ft^3
gal (USA)	0.833	gal (Br.)
gal	3.785	L
L	0.001	m^3
L	0.03532	ft^3
L	0.22	gal (Br.)
L	0.2642	gal (USA)
m^3	35.314	ft^3
m^3	1000	L

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- Reviewed many articles, papers and research studies for different authorities. Actively participated in or attended many local, regional and international conferences, congresses, seminars and workshops.
- Obtained the Sudan Engineering Society Prize for the Best Project in Civil Engineering, 7th June 1977. The Ministry of Irrigation Prize for Second Best Performance in 4th year Civil Engineering, 7th June 1977 and the Honourly Scarf for Enrichment of Knowledge, Khartoum University Press, February the 25th 1986, Abdallah Eltaib prize for the best published book, 2000.
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