Eastern
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HYDROGEOLOGY

Problems with Solutions

Nandipati Subba Rao

HYDROGEOLOGY
Problems with Solutions

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2016

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Nandipati Subba Rao

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ISBN-978-81-203-5278-0

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Published by Asoke K. Ghosh, PHI Learning Private Limited, Rimjhim House, 111, Patparganj Industrial Estate, Delhi-110092 and Printed by Mudrak, 30-A, Patparganj, Delhi-110091.

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Foreword

It is a common observation that there is a dearth of textbooks on geology as compared to the textbooks on the other major branches of science such as physics, chemistry, biology, etc. This opinion was held for a long time. However, in the recent years, there is a break in this trend, and now, there is plethora of books on geology, satisfying the needs of students, professionals, scientists and covering the international, regional, national and local level interests. This is largely due to drastic change in our understanding of the subject, rapid development of interdisciplinary sciences, increase in number of people opting geology as the subject of specialisation, the competing industry of publishing, encouragement and promotion of publication by the government, and most importantly, application of geological sciences in various facets of human life. Many of the textbooks are made available on Internet either on payment basis or free of charge. All these aspects make the knowledge easily available, which was once a great hindrance! In spite of this, it is hard to find a textbook, which covers the numerical problem-solving aspect in the field of hydrogeology. In this regard, the present textbook by Prof. Nandipati Subba Rao is gladly received by the entire community of science and technology, especially by the people who are involved in water resources studies. The textbook covers full spectrum of hydrogeology. In each chapter, the author has provided several worked-out examples, covering various aspects of the subject. As the textbook also provides the definitions and formulae, the reader will not feel the need of any other textbook to solve the problem(s). Thus, this book is a comprehensive text and is useful for the students studying hydrogeology and the professionals associated with this field.

I know Prof. Subba Rao when he was pursuing M.Sc. Geology at Andhra University, and later on, he earned another Master's degree in Geo-engineering and Resource Development followed by Ph.D. degree in Environmental Hydrogeology from the same university. He always used to show a great zeal of interest in research, and this is evident from his scientific publication record as well as from his awards.

I am sure this textbook will become a favourite book of all those who are connected with hydrogeology for a long time!

U. Aswathanarayana

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Preface

Numerical data is the heart of empirical models, which plays a key role in validating/refuting a theoretical proposition. The traditional learning in any discipline starts with observations in natural processes, translation of most of them into a mathematical model and solving with a chosen procedure from plethora of statistical/natural computing algorithms. But, the solution of real-life tasks requires state-of-the-knowledge in view of cost/benefit ratio. This demands *in-situ* learning or learning through knowledge transfer. The gap between textbook information and solving real-life tasks is bridged through research pedagogy of going through the details of computations at least for relevant problems of increasing complexity. This is applicable to every branch of Science, and Earth Sciences are not an exception. Many textbooks on mineralogy and petrology provide worked-out examples based on the mineral formula and petrochemical calculations. Although textbooks on hydrogeology incorporate details on algorithms and formulae to calculate various hydrogeological properties, books focusing on calculation part are rare. There is no textbook available in the market, which exclusively deals with various hydrogeological problems. Further, in the recent years, there is an increasing trend to adopt methods for groundwater exploitation for potable, agricultural and industrial purposes, which also demand for a textbook based on hydrogeological calculations. Thus, I conceived the idea to write a textbook focusing on numerical hydrogeological problems, including stepwise solutions, which is apt to undergraduate and postgraduate students, teachers, scientists, researchers and technical staff. Since hydrogeology is a multidisciplinary approach, this textbook also serves the needs of other disciplines like geophysics, meteorology, civil engineering, geography, etc.

This book is divided into ten chapters, viz. hydrological cycle, morphometric analysis, hydrological properties, groundwater flow, well hydraulics, well design and construction, groundwater management, seawater intrusion, groundwater exploration, and groundwater quality, thus covering a wide spectrum of disciplines. Each section is developed in a logical manner, retaining easy-to-read and ready-to-practice flavour. The information given in appendices is taken from standard tables and glossary is included as a ready reckoner.

I am indebted to Prof. G. Krishna Rao, my Research Director, who created scientific zeal in me, for his relentless brain-storming discussions, and most importantly, for his unstinted shower of blessings.

I appreciate the forbearance of Smt. N.V.N.L. Suseela and the overwhelming love of my daughters, Mrs. G. Pallavi and Ms. Srinavya, in changing this dream into reality.

Nandipati Subba Rao

1

Hydrological Cycle

PROBLEM 1 Rainfall of 770, 870, 930, 1,060, 1,050 and 1,370 mm is recorded at rain-gauge stations of *A*, *B*, *C*, *D*, *E* and *F* in a river basin. Estimate the average areal depth of rainfall over the river basin, using (a) arithmetic average method, (b) Thiessen polygon method and (c) isohyetal method, with neat sketches, wherever necessary.

Key Concept Precipitation is the atmospheric discharge of water (hail, snow and rain) on the Earth's surface. It is recorded by gauges. The distribution of the precipitation (mainly rainfall) data from a number of stations depicts an overall trend of intensity of the precipitation. This is of great practical interest in groundwater studies, irrigation and other disciplines concerned with the use and regulation of water on the land.

Data of the given problem

Rain-gauge stations = *A*, *B*, *C*, *D*, *E* and *F* (Figure 1.1; Table 1.1)
Corresponding rainfall = 770, 870, 930, 1,060, 1,050 and 1,370 mm (Figure 1.1; Table 1.1)

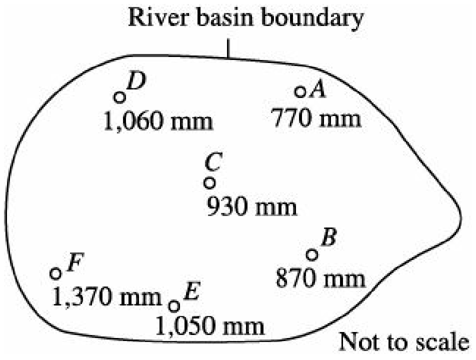


FIGURE 1.1 Location of the rain-gauge stations (*A* to *F*) and corresponding rainfall (mm).

Solution

(a) Arithmetic average method: A sum of all the numbers in the series divided by the count of all numbers in the series (Table 1.1).

$$A = \frac{1}{n}\sum_{i=1}^{n} a \qquad (1.1)$$

where,

A = arithmetic average

$a_1 \ldots a_n$ = sum of the numerical values of each observation

n = total number of observations

TABLE 1.1 Rain-gauge Stations and Corresponding Rainfall

Rain-gauge stations	*Rainfall, P* (mm)
A	770
B	870
C	930
D	1,060
E	1,050
F	1,370
$n = 6$	$\Sigma P = 6{,}050$

$$P_{\text{average}} = \frac{\Sigma P}{n} \qquad (1.2)$$

where,

P_{average} = average depth of the rainfall over the area (mm)

$\sum P$ = sum of the rainfall amounts (mm) at individual rain-gauge stations

n = number of rain-gauge stations in the area

Therefore,

$$P_{\text{average}} = \frac{6{,}050}{6}$$

$$= 1{,}008.33 \text{ mm or } 10.08 \text{ cm}$$

(b) Thiessen polygon method: In this method, the basin is divided into six polygons by

drawing lines between adjacent pairs of the rain-gauge stations and bisecting the lines perpendiculars (Figure 1.2). The areas within each polygon and the resultant data are calculated (Table 1.2).

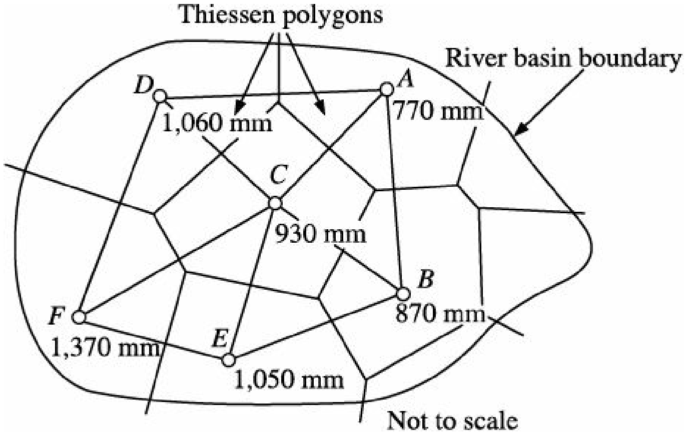


FIGURE 1.2 Location of rain-gauge stations (*A* to *F*) and corresponding rainfall (mm) with Thiessen polygons.

TABLE 1.2 Rain-gauge Stations, Rainfall and Area of Influential Polygon

Rain-gauge stations	*Rainfall, P* (mm)	*Area of influential polygon, A* (km^2)	*Product, P* × *A* (mm)
A	770	910	7,007
B	870	580	5,046
C	930	630	5,859
D	1,060	710	7,526
E	1,050	560	5,880
F	1,370	700	9,590
		$\Sigma A = 4{,}090$	$\Sigma PA = 40{,}908$

$$P_{\text{average}} = \frac{\Sigma PA}{\Sigma A} \tag{1.3}$$

where,

P_{average} = average depth of the rainfall over the area (mm)

$\sum PA$ = product of rainfall and area of the influential polygon

$\sum A$ = total area of the influential polygon (km^2)

Therefore, $$P_{\text{average}} = \frac{40{,}908}{4{,}090} = 10{,}002 \text{ mm or } 10.00 \text{ cm}$$

(**c) Isohyetal method:** Isohyetal lines or isohyets, which join all points that receive the same amount of rainfall, are drawn (Figure 1.3) and the areas between the isohyets and their products are calculated (Table 1.3).

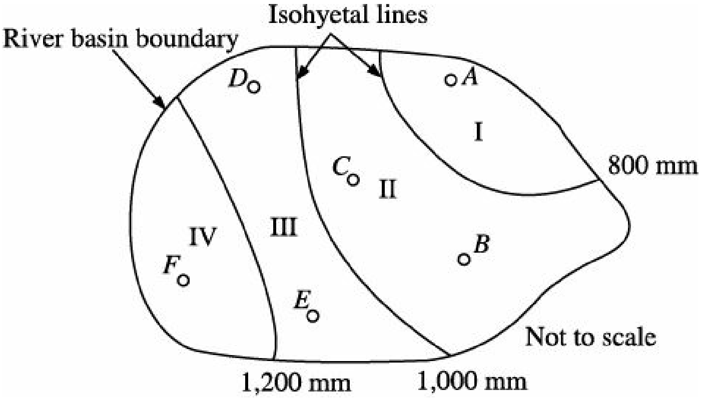


FIGURE 1.3 Location of rain-gauge stations (*A* to *F*) and corresponding rainfall (mm) with isohyetal lines.

TABLE 1.3 Isohyetal Range, Rainfall and Area between Isohyets

Zone	*Isohyetal range* (mm)	*Average rainfall, P* (mm)	*Area* (*A*) *between isohyets* (km^2)	*Product, P × A* (mm)
I	600 – 800	700	590	4,130
II	800 – 1,000	900	1,430	12,870
III	1,000 – 1,200	1,100	870	9,570
IV	1,200 – 1,400	1,300	660	8,580
		$\Sigma P = 4{,}000$	$\Sigma A = 3{,}550$	$\Sigma PA = 35{,}150$

$$P_{\text{average}} = \frac{\Sigma PA}{\Sigma A} \tag{1.4}$$

where,

P_{average} = average depth of the rainfall over the area (mm)

ΣPA = product of rainfall and area of the influential polygon

ΣA = total area of the influential polygon (km^2)

Therefore, $$P_{\text{average}} = \frac{35{,}150}{3{,}550} = 9{,}901 \text{ mm or } 9.90 \text{ cm}$$

PROBLEM 2 Estimate the (a) three-year and (b) five-year trend of the moving average curve for the data of 11 years rainfall (Table 2.1) and also draw the (c) moving average curve for understanding their overall trend pattern with a suitable sketch.

Key Concept Moving average is a statistical calculation. When calculating the successive values, a new value comes into the sum and an old value drops out. Generally, if the rainfall at a place over a number of years is drawn as a bar graph, it cannot show any trend in the rainfall due to wide variation in the consecutive years. Thus, to know the general trends (short-term and long-term cycles) in the rainfall pattern, the averages of three or five consecutive years are computed progressively by moving the group averaged, one year at a time.

Data of the given problem

TABLE 2.1 Year and Rainfall

Year	*Rainfall* (cm)
1980	80
1981	79
1982	81
1983	76
1984	65
1985	75
1986	66
1987	78
1988	74
1989	70
1900	76
Average	74.55

Solution

$$MA = \frac{1}{n}\sum_{i=0}^{n-1} pm - 1 \tag{2.1}$$

where,

MA = moving average

pm = data of the corresponding time

n = total number of observations

$$\textbf{(a) Three-year moving average} = \frac{a+b+c}{3} \tag{2.2}$$

where,

a, b and c = First, second and third years. In each successive calculating procedure, a, b and c come as first, second and third order, respectively (Table 2.2).

TABLE 2.2 Calculation of Three-year Moving Averages

Year	*Rainfall* (cm)									
1980	80	*a*								
1981	79	*b*	*a*							
1982	81	*c*	*b*	*a*						
1983	76		*c*	*b*	*a*					
1984	65			*c*	*b*	*a*				
1985	75				*c*	*b*	*a*			
1986	66					*c*	*b*	*a*		
1987	78						*c*	*b*	*a*	
1988	74							*c*	*b*	*a*
1989	70								*c*	*b*
1900	76									*c*
Moving average		80.00	78.67	74.00	72.00	68.87	73.00	72.67	74.00	73.33

(b) Five-year moving average = $$\frac{a+b+c+d+e}{5} \tag{2.3}$$

where,

a, b, c, d and e = First, second, third, fourth and fifth years. In each successive calculating procedure, a, b, c, d and e come under first, second, third, fourth and fifth order, respectively (Table 2.3).

TABLE 2.3 Calculation of Five-year Moving Averages

Year	*Rainfall* (cm)							
1980	80	*a*						
1981	79	*b*	*a*					
1982	81	*c*	*b*	*a*				
1983	76	*d*	*c*	*b*	*a*			
1984	65	*e*	*d*	*c*	*b*	*a*		
1985	75		*e*	*d*	*c*	*b*	*a*	
1986	66			*e*	*d*	*c*	*b*	*a*
1987	78				*e*	*d*	*c*	*b*
1988	74					*e*	*d*	*c*
1989	70						*e*	*d*
1900	76							*e*
Moving average		76.20	75.20	72.60	72.00	71.60	72.60	72.80

(c) Moving average curve: A moving average curve (Figure 2.1) is drawn by plotting the years on x-axis, and rainfall on y-axis on a simple arithmetic graph.

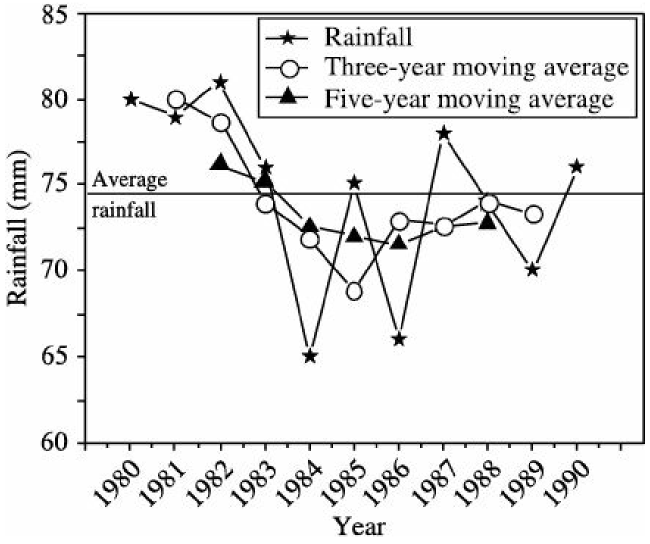


FIGURE 2.1 Moving average curve.

The moving average curve (Figure 2.1) shows the year-wise rainfall, average rainfall, three-year moving average rainfall and five-year moving average rainfall. The curve smoothens out the extreme variations, which indicate the trend pattern more clearly. For example, there is a wide variation in the consecutive years in the three-year moving average rainfall trend, while that is not in the case of the five-year trend. Thus, the moving average curve can be useful in identifying the short-term and long-term trends of the rainfall at a place.

PROBLEM 3

a. Estimate the water deficiency and water surplus for the data of meteorological data (Table 3.1).
b. Draw the water balance graph.
c. Compute the climatic type of an area.

Key Concept *Precipitation* (*P*) is mainly rainwater, which falls to or condenses on the ground. A sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere is called *evapotranspiration* (*E*). *Potential evapotranspiration* (*PE*) is an amount of evaporation that will occur if a sufficient water source is available. The quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration is referred to as *actual evapotranspiration* (*AE*). The quantity of water in excess of actual evapotranspiration from precipitation is termed as *soil moisture utilisation* (*SMU*). *Water deficit* (*WD*) is an amount of water by which potential evapotranspiration exceeds actual evapotranspiration. *Water surplus* (*WS*) is an amount or quantity of water in excess of what is needed. This describes the water balance, i.e., flow of water in and out of a system, which helps in the water management studies.

Data of the given problem

TABLE 3.1 Meteorological Data (mm) of Krishna River Basin (Subrahmanyam et al. 1980)

Month	*P*	*PE*	*AE*
January	6	86	45
February	4	88	31

March	9	118	30
April	32	167	46
May	57	155	63
June	165	152	152
July	294	90	90
August	233	125	125
September	159	114	114
October	123	120	120
November	45	88	84
December	7	72	52

Solution

(a) Water deficit and water surplus: Calculation procedure of the water deficit and water surplus from the data of *P*, *PE* and *AE* is shown in Table 3.2, following Thornthwaite's formula (1948).

TABLE 3.2 Water Balance (Data in mm)

Month	*P*	*PE*	*AE*	*SMU*	*WD*	*WS*
	(*a*)	(*b*)	(*c*)	(*d* = *c* – *a*)	(*e* = *b* – *c*)	(*f* = *a* – *c*)
January	6	86	45	39	41	–
February	4	88	31	27	57	–
March	9	118	30	21	86	–
April	32	167	46	14	121	–
May	57	155	63	6	92	–
June	165	152	152	–	–	13
July	294	90	90	–	–	204
August	233	125	125	–	–	108
September	159	114	114	–	–	45
October	123	120	120	–	–	3
November	45	88	84	39	4	–
December	7	72	52	45	20	–
Total	1,134	1,375	952	191	423	373

(b) Water balance graph: It is graph that describes the flow of water in and out of a system.

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

where,

P = precipitation

Q = runoff

E = evapotranspiration

$\Delta \boldsymbol{S}$ = change in storage in soil or in the bedrock

A water balance graph (Figure 3.1) is drawn by plotting the months on x-axis, and P, PE and AE on y-axis on a simple arithmetic graph.

The water balance study (Table 3.2 and Figure 3.1) shows that the water need (*PE*, 1,375 mm) is higher than the water supply (*P*, 1,134 mm) by rainfall. There is a water deficiency (*WD*, 423 mm) from November to May and a water surplus (*WS*, 373 mm) from June to October. There is soil moisture utilisation (*SMU*, 191 mm) caused by excess of actual evapotranspiration (*AE*, 351 mm) over precipitation (*P*, 160 mm) from November to May from storage.

The *WD* indicates the amount of water needed for supplemental irrigations in agricultural operations, adjustment of crop calendar so that the harvest will precede drought, and crop rotation to improve the soil structure and increase the soil moisture storage capacity. Crop yields can be increased, if the moisture deficiency is avoided.

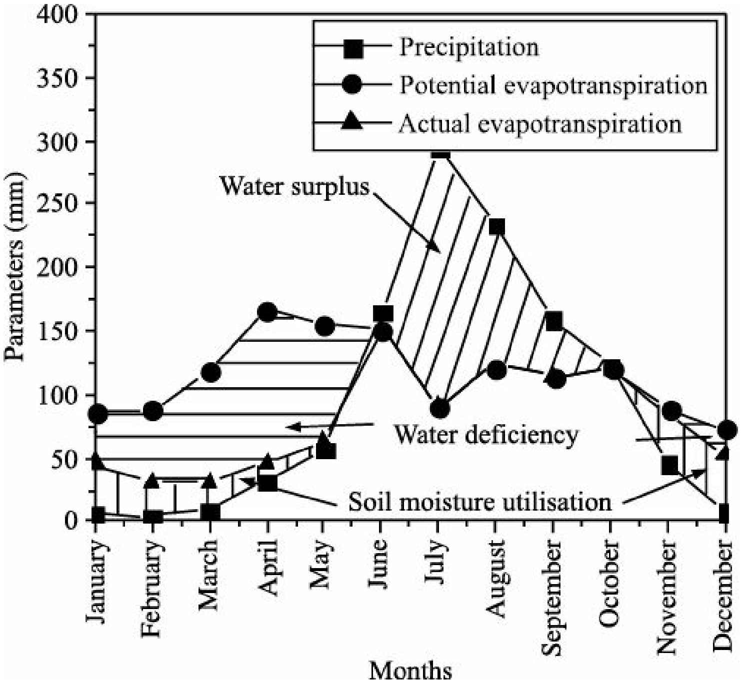


FIGURE 3.1 Water balance.

(c) Climatic type: It indicates the weather conditions prevailed in an area in general or over a long period. The Köppen system recognises five major climatic types—1. tropical climate (all months have average temperatures above 18°C), 2. dry climate (with deficient precipitation during most of the year), 3. moist mid-latitude climates with mild winters, 4. moist mid-latitude climates with cold winters and 5. polar climates (with extremely cold winters and summers).

(i) *Humidity index* **(l_h)***:* It is the index of amount of water vapour in the air, which is defined as the ratio of annual water surplus to annual water need and is expressed in percentage (%) [Eq. (3.1)].

$$(l_h) = \frac{AWS}{AWN} \times 100 \tag{3.1}$$

where,

AWS = annual water surplus (mm)

AWN = annual water need (mm)

Therefore,
$$l_h = \frac{375}{1{,}376} \times 100$$
$$= 27.25\%$$

(ii) *Aridity index (l_a):* It is the degree of dryness of the climate at a given location, which is the ratio of annual water deficit to annual water need that is expressed in percentage (%); [Eq. (3.2)].

$$(l_a) = \frac{AWD}{AWN} \times 100 \tag{3.2}$$

where,

AWD = annual water deficit (mm)

Therefore,
$$l_a = \frac{418}{1{,}376} \times 100$$
$$= 30.38\%$$

(iii) *Moisture index (l_m):* It is the ability of soil to supply moisture to plants. It is a difference amount between the humidity index and the aridity index [Eq. (3.3)], which is expressed in percentage (%).

- Thornthwaite and Mather's formula (1955) $= l_h - 0.6l_a$ (3.3)

  Therefore,
  $$l_m = 27.25 - (0.6 \times 30.38)$$
  $$= 9.02\%$$
- Mather and Carter's formula (1958) $= l_h - l_a$ (3.4)

  Therefore,
  $$l_m = 27.25 - 30.38$$
  $$= -3.13\%$$

The moisture index of the area varies from – 3.13% to 30.38%. Thus, the area comes under dry sub-humid climatic type (Tables 3.3 and 3.4).

TABLE 3.3 Moisture Index and Climate Types (Thornthwaite and Mather, 1955)

Symbol	*Climatic type*	*Moisture index* (%)
A	Per-humid	100 and above
B	Humid	
B4		80 to 99
B3		60 to 79
B2		40 to 59
B1		20 to 39
C_2	Moist sub-humid	0 to 19
C_1	Dry sub-humid	–19 to 0
D	Semi-arid	–39 to –20
E	Arid	–40 and below

TABLE 3.4 Moisture Index and Climate Types for Dry Climates Alone (Mather and Carter, 1958)

Symbol	*Climatic type*	*Moisture index* (%)
C_1	Dry sub-humid	–33.3 to 0
D	Semi-arid	–66.5 to –33.4
E	Arid	–66.6 and below

PROBLEM 4 A catchment area of 20 km^2 has an annual rainfall of 900 mm, sandy soil content of 20% and temperature of 16°C. Estimate the (a) runoff, (b) runoff percentage and (c) groundwater recharge.

Key Concept A catchment area is a hydrological unit (Figure 4.1). Each drop of rainfall falling into a catchment area eventually ends up in the same river going to the sea, if it does not evaporate. However, it can take a very long time. A part of water that flows over land as surface water is termed as *runoff*. If the runoff is expressed in percentage (%), it is called *runoff percentage*. In a hydrologic process, rainwater moves downward through soil cover and reaches the water table. It is referred to as *groundwater recharge*. Whereas, a rainfall that occurs as surface water flow after evapotranspiration losses and losses to soil or groundwater is called *catchment water yield*.

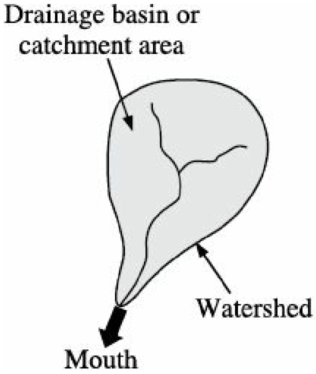


FIGURE 4.1 Catchment area.

Data of the given problem

Catchment area = 20 km^2

Rainfall = 900 mm or 90 cm or 0.9 m

Sandy soil content = 20%

Temperature = 16°C

Solution

(a) Runoff: It is a part of water that flows over land as surface water. It can be estimated, using the formulae like Barlow, Inglis, Khosla and Lacey [Eqs. (4.1) to (4.5)]. This is expressed in millimetre (mm).

(i) Barlow's formula (1915),

$$R = KP \tag{4.1}$$

where,

R = runoff (mm)
K = runoff coefficient (0.20, Table 4.1)
P = rainfall (mm)

Therefore,

$$R = 900 \times 0.20 = 180 \text{ mm}$$

TABLE 4.1 Barlow's (1915) Runoff Coefficient (K) Based on Average Monsoon Conditions

Class	Type of catchment	Runoff coefficient (K)
A	Flat, cultivated and black cotton soil	0.10
B	Flat, partly cultivated, various soil	0.15
C	Average catchment	0.20
D	Hills and plains with little cultivation	0.35
E	Very highly and steep with hardly any cultivation	0.45

(ii) Inglis's formula (1946)

(ii) Inglis's formula (1946)

- R in non-ghat area = $0.85\ P - 304.8$ (4.2)
- R in ghat area = $\dfrac{P(P - 177.8)}{2,540}$ (4.3)

  where,
  R = runoff (mm)
  P = rainfall (mm)

- R in non-ghat area = $(0.85 \times 900) - 304.8 = 460.20$ mm
- R in ghat area = $\dfrac{900\,(900 - 177.8)}{2,540} = 255.90$ mm

(iii) Khosla's formula (1949), $R = P - [(22.8\ T - 40.57)]$ (4.4)

where,

R = runoff (mm)
P = rainfall (mm)
T = annual temperature (°C)

Therefore,

$$R = 900 - [(22.8 \times 16) - 405.70)]$$
$$= 129.50 \text{ mm}$$

(iv) Lacey's formula (1957),

$$R = \frac{P}{1 + \dfrac{304.8}{P}\left(\dfrac{F}{S}\right)} \tag{4.5}$$

where,
R = runoff (cm)
P = rainfall (cm)
F = monsoon duration factor (1, Table 4.2)
S = catchment factor (1, Table 4.3)

Therefore,

$$R = \frac{90}{1 + \dfrac{304.8 \times 1}{90 \times 1}}$$
$$= 20.515 \text{ cm or } 205.15 \text{ mm}$$

TABLE 4.2 Lacey's (1957) Classification of Monsoon and Duration Factor (*F*)

Classification of monsoon	*Value of F*
Very short	0.50
Standard length	1.00
Very long	1.50

TABLE 4.3 Lacey’s (1957) Catchment Factor (*S*)

Class	*Characteristics*	*Catchment factor (S)*
A	Flat, cultivated, absorbent soil	0.25
B	Flat, partly cultivated, stiff soil	0.60
C	Average catchment	1.00
D	Hills, with plains with little cultivation	1.70
E	Very highly steep with little or no cultivation	3.45

The average runoff of the above formulae (180 + 460.20 + 255.90 + 129.50 + 205.15) is 246.15 mm. This is near to the value of 255.90 mm calculated from the ghat area Inglis’s formula. Thus, this can be taken into consideration.

(**b) Runoff percentage:** It is an expression of runoff in percentage (%), depending on the annual rainfall.

Binnie’s percentage (1872) = 34% for 900 mm of the annual rainfall (Table 4.4)

TABLE 4.4 Binne’s (1872) Runoff Percentage

Annual rainfall (mm)	*Runoff* (%)
500	15
600	21
700	25
800	29
900	34
1,000	38
1,100	40

(c) Groundwater recharge: Groundwater recharge is a hydrologic process, where water moves downward from surface water to groundwater. It is estimated using the formulae like Bhattacharya, Krishna Rao, Chaturvedi, Sehgal, Radhakrishna and Datta et al. [Eqs. (4.6) to (4.11)]. This is expressed in millimetre (mm).

(i) Bhattacharya's formula (1954), $P = 3.47\ (R - 38)^{0.4}$ (4.6)

where,

P = rainfall penetration
R = annual rainfall (cm)

Therefore, $P = 3.47\ (90 - 38)^{0.4}$
$= 16.86$ cm or 168.60 mm

(ii) Krishna Rao's formula (1970), $G = K(P - X)$ (4.7)

where,

G = groundwater recharge (mm)
K = Constant (0.25 for sandy soil; Table 4.5)
X = annual rainfall (mm), which yields no groundwater recharge
P = precipitation (mm)

Therefore, $G = 0.25\ (900 - 400)$
$= 125$ mm

TABLE 4.5 Krishna Rao's (1970) Relationship of Rainfall (P) with Groundwater Recharge (G)

Area with rainfall range
$G = 0.20\ (P - 400)$ for an area with an annual rainfall (P) in between 400 and 600 mm
$G = 0.25\ (P - 400)$ for an area with an annual rainfall (P) in between 600 and 1,000 mm
$G = 0.30\ (P - 500)$ for an area with an annual rainfall (P) in between 1,000 and 2,000 mm
$G = 0.35\ (P - 600)$ for an area with an annual rainfall (P) of more than 2,000 mm

(iii) Chaturvedi's formula (1973), $W = 13.93\ (P - 381)^{0.4}$ (4.8)

where,

W = groundwater recharge (mm)
P = annual rainfall (cm)

Therefore, $W = 13.93\ (900 - 381)^{0.4} = 169.83$ mm

(iv) Sehgal's formula (1973), $W = 12.6\ (P - 406.4)^{0.5}$ (4.9)

where,

W = groundwater recharge (mm)
P = annual rainfall (mm)

Therefore, $W = 12.6\ (900 - 406.4)^{0.5} = 279.94$ mm

(v) Radhakrishna's formula (1974), $G = \frac{P \times 10}{100}$ (4.10)

where,

G = groundwater recharge (mm)
P = rainfall (mm)

Therefore, $$G = \frac{900 \times 10}{100} = 90 \text{ mm}$$

(vi) Datta et al.'s formula (1980), $$Re = 0.11\,(P - 41.8) \tag{4.11}$$

where,

Re = estimated recharge (cm)
P = rainfall (cm)

Therefore, $$\begin{aligned} Re &= 0.11\,(90 - 41.8) \\ &= 53.02 \text{ cm} \end{aligned}$$

The average groundwater recharge of the above formulae (168.60 + 125 + 169.83 + 279.94 + 90 + 53.02) is 147.73 mm. This is near to the value of 168.60 mm and 169.83 mm calculated from respective Bhattacharya's and Chaturvedi's formulae. Thus, these can be taken into consideration.

(d) Catchment water yield: It is the rainfall that occurs as surface water flow after evapotranspiration losses and losses to soil or groundwater. It is calculated through rational method.

Rational method (1931): This represents a product of runoff coefficient, area of catchment and precipitation [Eq. (4.12)], which is expressed in square kilometre (km^2).

$$\text{Catchment water yield} = CAP \tag{4.12}$$

where,

C = runoff coefficient (0.25 for sandy soil, Table 4.6)
A = area of the catchment (km^2)
P = precipitation (mm)

TABLE 4.6 Richard's (1981) Runoff Coefficients (C) for Various Types of Catchments

Type of catchment	*Runoff coefficient (C)*	
	Range	*Average*
Rocky and impermeable	0.80 to 1.00	0.90
Slightly permeable, bare	0.60 to 0.80	0.70
Cultivated or covered with vegetation	0.40 to 0.60	0.50
Cultivated absorbent soil	0.30 to 0.40	0.35
Sandy soil	0.20 to 0.30	0.25
Heavy forest	0.10 to 0.20	0.15

PROBLEM 5 In an area, the infiltration rates for different time intervals after the

beginning of the storm are shown in Table 5.1. The total rainfall is 900 mm. Determine the (a) total infiltration loss, (b) total rain and (c) excess rain, using Horton's method.

Key Concept A product of precipitation with time is called *total rain*, while an amount of precipitation in excess of the total infiltration loss is termed as *excess rain*. *Infiltration* is the process by which water on the ground surface enters the soil. The rate of infiltration is a measure of the rate at which soil is able to absorb rainfall or irrigation, which is affected by soil characteristics, including ease of entry, storage capacity and transmission rate through the soil. The soil texture and structure, vegetation types and cover, water content of the soil, soil temperature and rainfall intensity—all play an important role in controlling infiltration rate and capacity. The higher the infiltration rate, the lower is the runoff and the greater is the groundwater recharge.

Data of the given problem

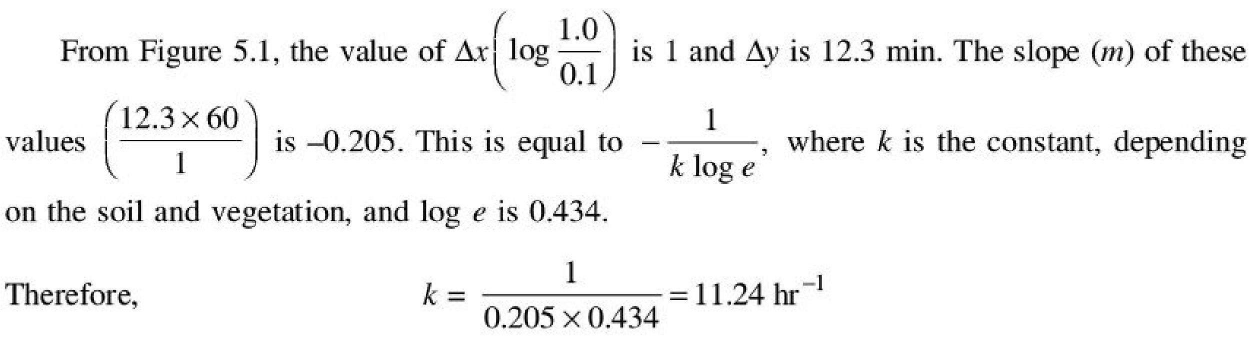
TABLE 5.1 Data on Time and Infiltration Rate

Time (t, min)	*Infiltration rate* (f_t, cm/h)	*Infiltration rate* (f_t) – *Final infiltration rate* (f_c, cm/h)
1	4.20	2.69
2	3.70	2.19
3	3.40	1.89
4	3.00	1.49
5	2.80	1.29
6	2.60	1.09
8	2.26	0.75
10	2.02	0.51
12	1.86	0.35
14	1.77	0.26
16	1.68	0.17
18	1.62	0.11
20	1.59	0.08
22	1.56	0.05
24	1.54	0.03
26	1.53	0.02
28	1.52	0.01

30	1.51 (f_c)	0.00

Solution

The values of infiltration rate (f_t) – final infiltration rate (f_c), which are shown in Table 5.1, are plotted against time (t) in a semi-logarithmic graph (Figure 5.1).



From Figure 5.1, the value of $\Delta x\left(\log\dfrac{1.0}{0.1}\right)$ is 1 and Δy is 12.3 min. The slope (m) of these values $\left(\dfrac{12.3\times 60}{1}\right)$ is –0.205. This is equal to $-\dfrac{1}{k\log e}$, where k is the constant, depending on the soil and vegetation, and log e is 0.434.

Therefore, $$k = \frac{1}{0.205\times 0.434} = 11.24\ \text{hr}^{-1}$$

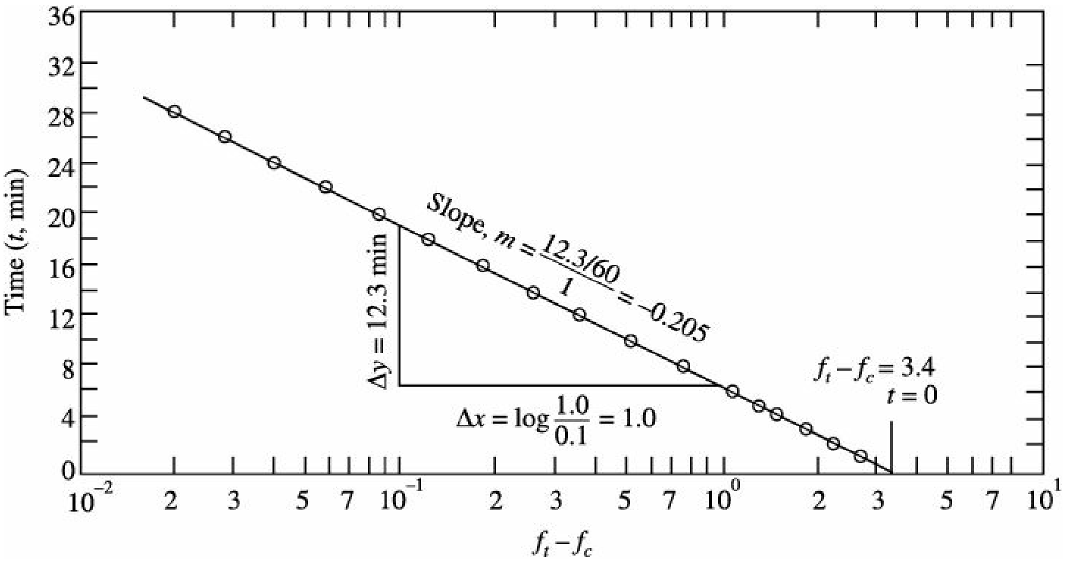


FIGURE 5.1 Data of $f_t - f_c$ versus T.

From Figure 5.1, when time (t) = 0, then the infiltration rate (f_t) – final infiltration rate (f_c) is 3.4. This is equal to $f_0 - f_c$ (since $f = f_0$ when $t = 0$)

Therefore, initial rate of infiltration (f_0) = 3.4 + 1.51 = 4.91 cm/h

According to Horton’s equation (1933), f, infiltration starts at a constant rate (f_0), and decreases exponentially with the time (t), as shown in Eq. (5.1). After some time, when the soil saturation level reaches a certain value, the rate of infiltration levels off to the rate f_c.

$$f = f_c + (f_0 - f_c)e^{-kt} \tag{5.1}$$

$$f = 1.51 + (4.91 - 1.51)\ e^{-kt}$$

or $$f = 1.51 + \frac{3.4}{e^{12t}}$$

(a) Total infiltration loss (F_b): This can be determined by integrating the Horton's equation for the duration of the storm (Eq. 5.2).

$$F_b = \int_0^t f\ dt = \int_0^{30/60} \left(1.51 + \frac{3.4}{e^{12t}}\right) dt \tag{5.2}$$

$$F_b = 1.51t + \frac{3.4}{-12e^{12t}}\Bigg|_0^{36/60}$$

$$F_b = \left[1.51 \times \frac{30}{60} - \frac{3.4}{12e^{12 \times 30/60}}\right] - \left[0 - \frac{3.4}{12e^0}\right]$$

$$F_b = 0.76 + \frac{3.4}{12}\left(1 - \frac{1}{e^6}\right)$$

Therefore, $$F_b = 0.76 + \frac{3.4}{12}\left(1 - \frac{1}{403}\right) = 0.88\ \text{cm}$$

(b) Total rain (P): It is the product of precipitation (rainfall) with time [Eq. (5.3)], which is expressed in centimetre (cm).

$$P = P \times \frac{t}{60} + P \times \frac{t}{60} + P \times \frac{t}{60} \tag{5.3}$$

$$P = 6 \times \frac{5}{60} + 7.5 \times \frac{10}{60} + 3.5 \times \frac{15}{60}$$

Therefore, $$P = 2.79\ \text{cm}$$

(c) Excess rain (P_{net}): It is the amount of precipitation (P) in excess of the total infiltration loss [F_b; Eq. (5.4)], which is expressed in centimetre (cm).

$$P_{\text{net}} = P - F_b \tag{5.4}$$

Therefore, $$P_{\text{net}} = 2.79 - 0.88 = 1.91\ \text{cm}$$

2

Morphometric Analysis

PROBLEM 6

a. Classify the type of pattern of the given in Figure 6.1 drainage basin (or watershed or catchment area.
b. Divide it into sub-basins.
c. Work out the morphometric characteristics—(i) basin length, (ii) basin width, (iii) basin area, (iv) basin perimeter, (v) stream order, (vi) stream numbers, (vii) bifurcation ratio, (viii) stream length, (ix) average stream length, (x) stream length ratio, (xi) length of overland flow, (xii) drainage density, (xiii) stream frequency, (xiv) drainage texture, (xv) drainage texture ratio, (xvi) constant of channel maintenance, (xvii) circulatory ratio, (xviii) elongation ratio, (xix) form factor, (xx) relief, (xxi) relief ratio, (xxii) relative relief and (xxiii) ruggedness number, with their role in the study of watershed.

Key Concept The morphometric analysis is a fluvial morphometry, which controls the development of a drainage basin. Thus, the basin analysis furnishes quantitative clues for an assessment of a watershed development. The morphometric characteristics cover three aspects—(a) linear aspect, (b) areal aspect and (c) relief aspect. The first one is related to the channel patterns of the drainage network, which includes stream order, stream number, bifurcation ratio, stream length, average length of streams, stream length ratio and length of overland flow; the second one is related to the spatial distribution of a number of significant attributes, which comprises stream frequency, drainage density, drainage texture, drainage texture ratio, constant of channel maintenance, circulatory ratio, elongation ratio and form factor; and the last one is related to the study of three-dimensional features of the basins, which include relief, relief ratio, relative relief and ruggedness number.

Data of the given problem

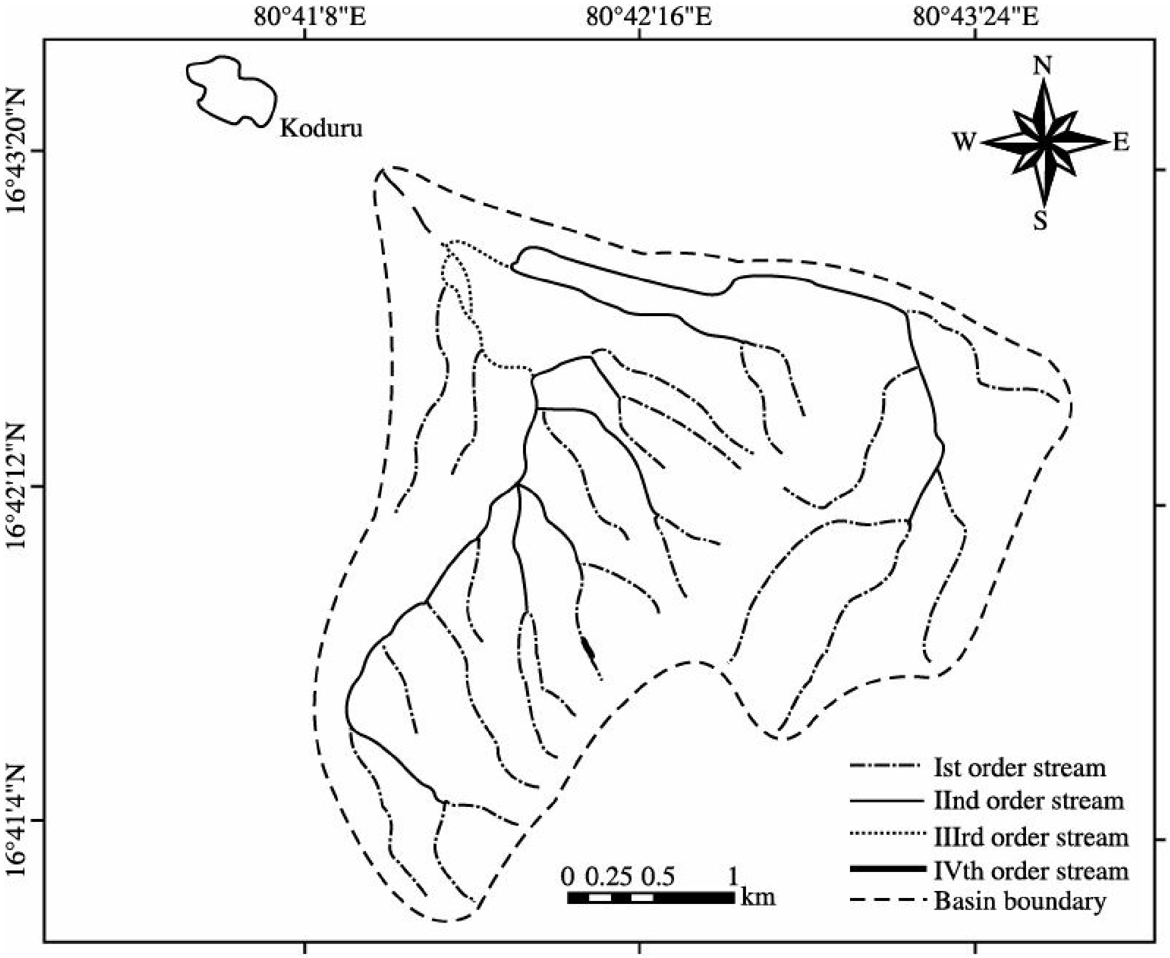


FIGURE 6.1 Drainage basin.

Solution

(a) Type of pattern of the drainage basin: The type of the drainage basin (Figure 6.1) comes under a sub-dendritic with a patch of sub-parallel drainage pattern, as it has many contributing streams (analogous to the twigs of a tree), which are then joined together into the tributaries of the main river (the branches and the trunk of the tree, respectively). The streams develop, where the river channel follows the slope of the terrain.

(b) Sub-divisions of the drainage basin: The drainage basin (Figure 6.1) is divided into two sub-basins, i.e., I and II, by separating the neighbouring water catchments, which show their own stream flows without intersecting with other catchment stream flows. Generally, the separation occurs along topographic ridges and hills.

(c) Morphometric characteristics: These are as follows:

(i) Basin length (L): It is the longest dimension of the basin parallel to the principal drainage line (km; Figure 6.2).

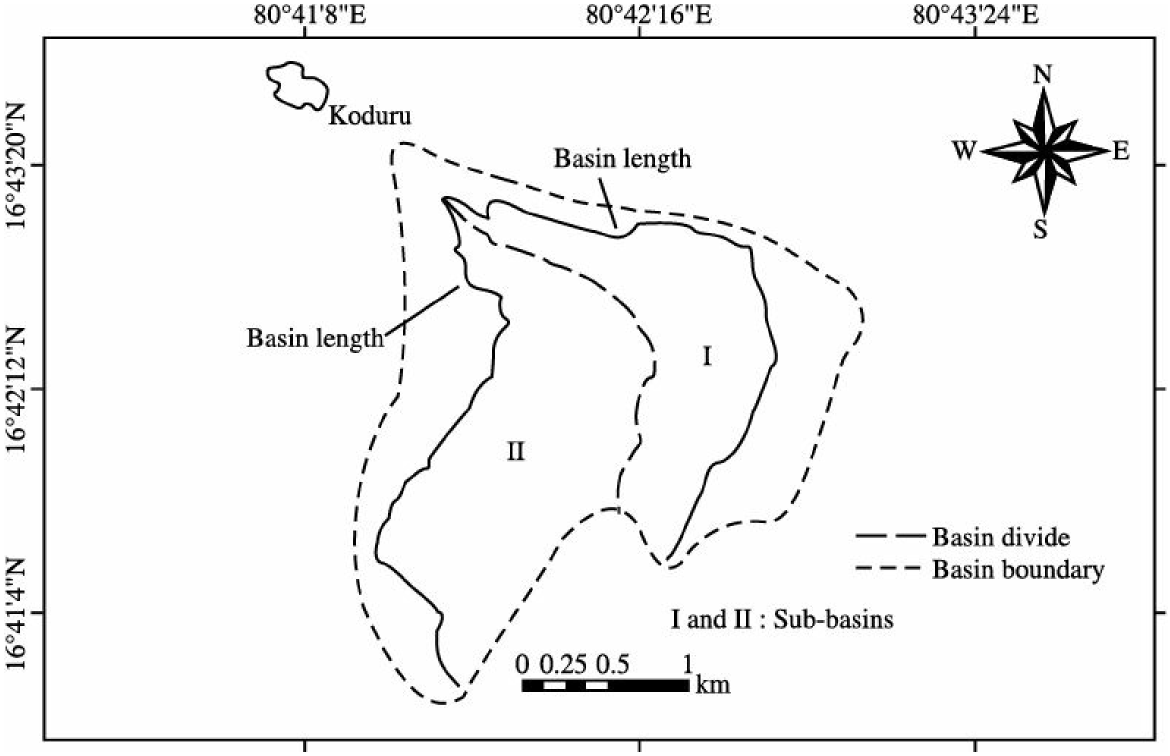


FIGURE 6.2 Length of the basin.

TABLE 6.1 Basin Length (*L*)

Sub-basin	*Basin length* (km)
Sub-basin I	4.49
Sub-basin II	4.56

Relatively, the sub-basin II shows the large length of the basin (4.56 km) compared to the sub-basin I (4.49 km; Table 6.1). The basin area is positively correlated with discharge of the basin, as the larger basins receive greater volume of precipitation (rainfall), and parameters such as basin length, stream length, which influence the runoff, are highly correlated with the basin area.

(ii) Basin width (W): It is the longest dimension of the basin perpendicular to

the principal drainage line (km; Figure 6.3).

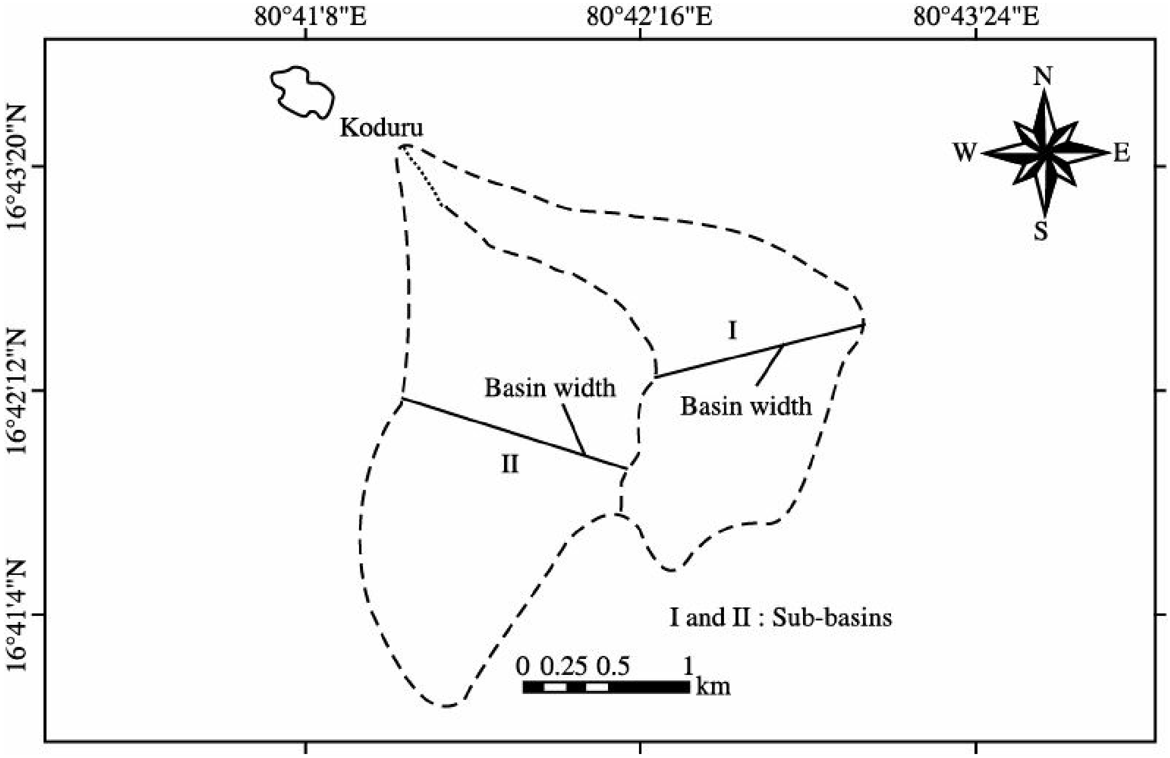


FIGURE 6.3 Width of the basin.

TABLE 6.2 Basin width (*W*)

Sub-basin	*Basin width* (km)
Sub-basin I	1.22
Sub-basin II	1.54

Comparatively, the width of the sub-basin II (1.54 km) is higher than that of the sub-basin I (1.22 km; Table 6.2). The width of the basin is also correlated positively with the discharge of the basin, which influences the runoff.

(iii) Basin area (A): The total area projected upon a horizontal plane contributes to cumulate of all order of basins (km^2), which is a product of length and width of the area (Eq. 6.1) and is expressed in square kilometres.

$$A = L \times W \tag{6.1}$$

where,

L = length of the basin (km)
W = width of the basin (km)

TABLE 6.3 Basin Area (*A*)

Sub-basin	*Basin area* (km^2)
Sub-basin I	5.47
Sub-basin II	7.01

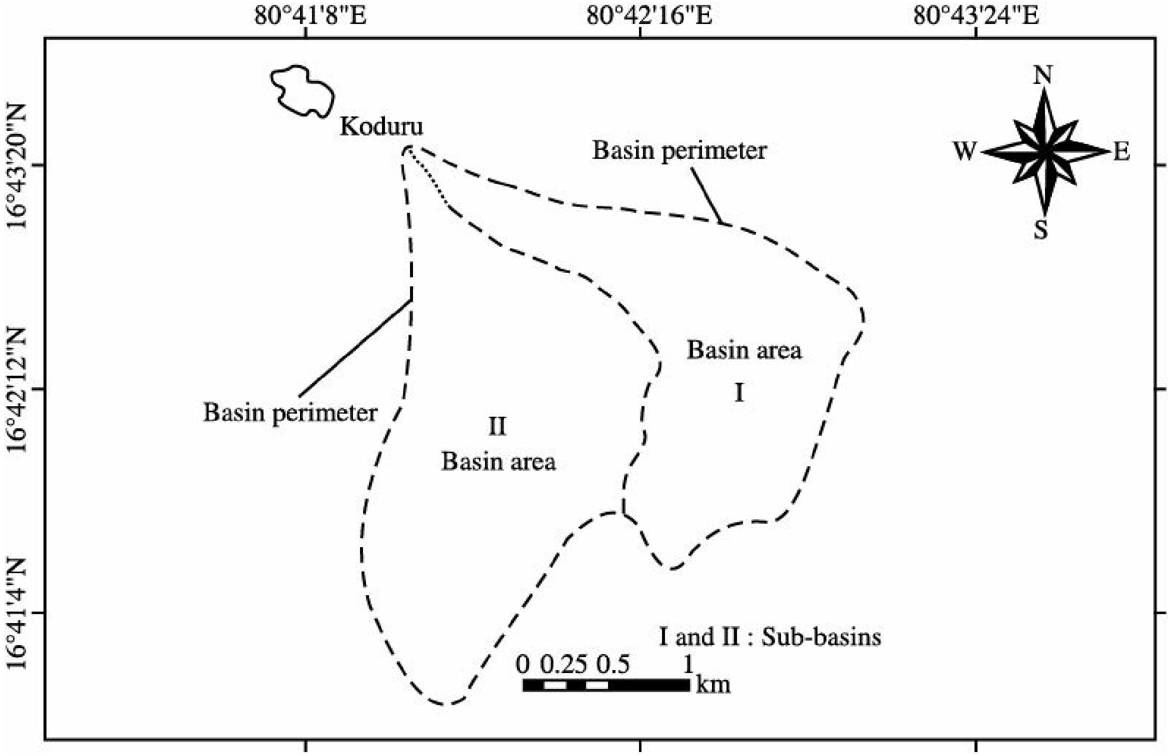


FIGURE 6.4 Basin perimeter and basin area.

The basin area is characterised by steeper slopes and intense erosional surfaces in the upstream area, causing higher runoff and lower permeability, and this condition supports lower infiltration. Thus, such area extends a greater distance and vice versa in the downstream area.

The areas of the sub-basin I and II are 5.47 and 7.01 km^2, respectively (Table 6.3). The area of the sub-basin II is 1.28 times higher than that of the sub-basin I. This appears to be caused by steeper slopes and intense erosional surfaces in the sub-basin II, causing higher runoff and lower permeability. This condition supports lower infiltration. Thus, the sub-basin II extends to a greater distance than that of the sub-basin I (Figure 6.3).

(iv) Basin perimeter (p): It is the length of the boundary of the basin (km, Figure 6.4)

TABLE 6.4 Basin Perimeter (*p*)

Sub-basin	*Basin perimeter* (km)
Sub-basin I	11.79
Sub-basin II	12.78

The basin perimeter depends on the slope of the area and the corresponding length of the streams. The perimeter of the sub-basin II (12.78 km) is slightly higher than that of the sub-basin II (11.79 km; Table 6.4), depending on the slope of the area and the corresponding length of the streams.

(v) Stream order (u): The flow of water in a specific way is called stream order. The flow of water is a measure of the position of a stream within the hierarchy of the drainage network. The first step in the basin analysis is to designate the stream orders (Horton, 1945; Strahler, 1952, 1957). The first-order streams, which originate from the topographic highs, are the unbranched tributaries and the second-order streams are formed after the junction of the first-order tributary, and so on [Figure 6.5(a)]. The main stream, which is the highest-order stream, receives the water from the entire lowest-order streams at the topographic lows. This is a fundamental basis for quantitative analysis of the drainage basin.

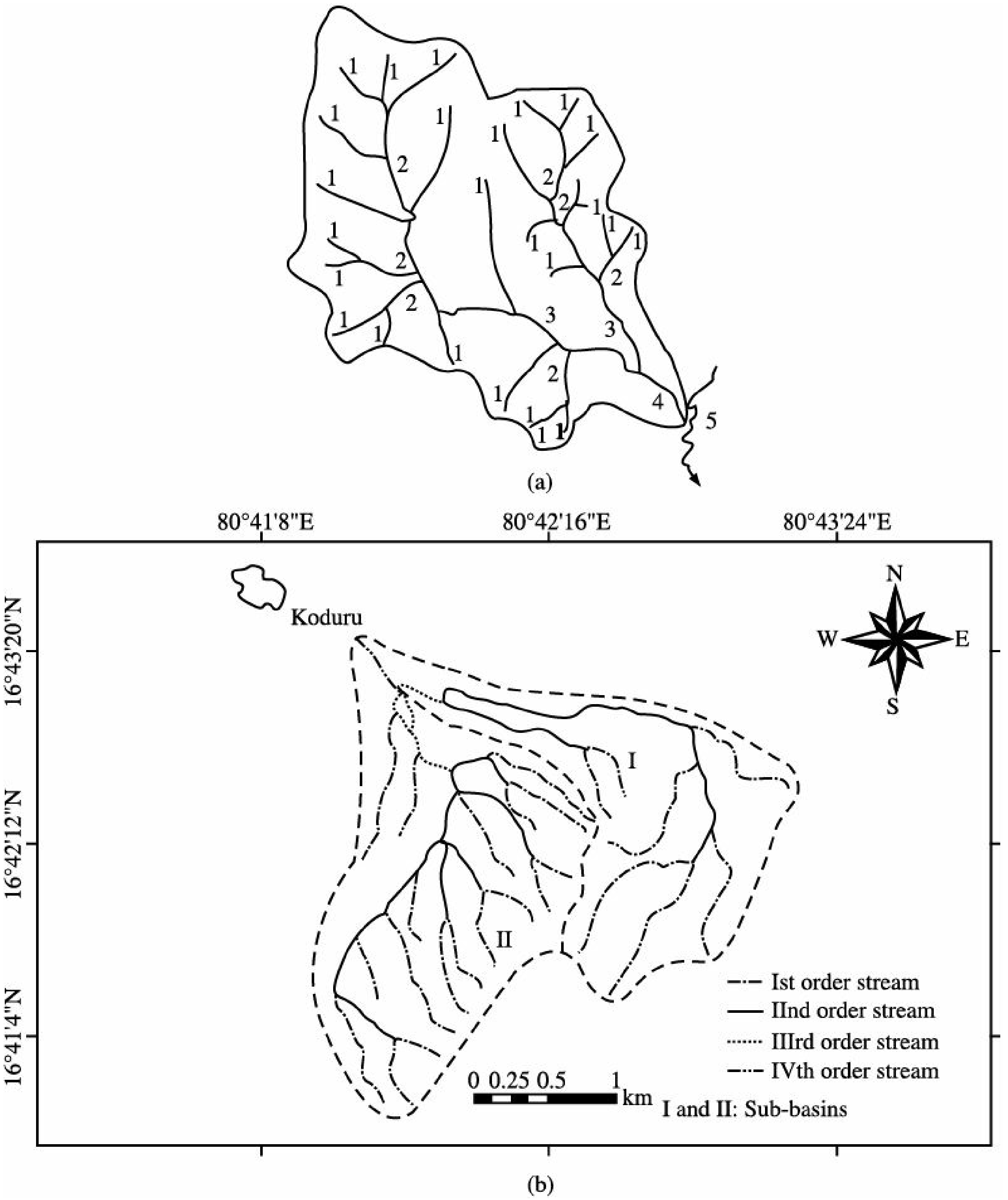


FIGURE 6.5 (a) Designation of the stream orders (after Strahler, 1957) and (b) stream orders.

TABLE 6.5 Stream Order (*u*)

Sub-basin I	*Sub-basin II*
I	I
II	II
III	III

–	IV

The stream orders in the sub-basins I and II are third and fourth, respectively [Table 6.5; Figure 6.5(b)]. Thus, the first-order streams are the unbranched tributaries and the second-order streams are formed after the junction of the first-order tributary and so on, as they originate from the topographic highs. The main stream receives the water from the entire lowest-order streams at the topographic lows, as it is the highest-order stream.

(vi) Stream numbers (Nu): It is the occurrence of the number of streams of the same stream order in a specified drainage basin (Strahler, 1957).

TABLE 6.6 Stream Numbers (*Nu*)

Stream order	*Stream numbers*	
	Sub-basin I	*Sub-basin II*
I	7	18
II	2	5
III	1	2
IV	–	1
	Σ10	Σ26

The first-order streams originate at topographic highs and the consequent streams join finally as a main-stream at topographic lows so that the first-order shows the higher number of streams and the main order shows the lower number of streams [Figure 6.5(b)]. Thus, the development of the streams is a function of surface runoff, which is controlled by slope, rock types, geological structures, climate (precipitation) and vegetation. Among these parameters, slope plays a vital role in the development of streams in the watershed, as most of the first-order streams originate from ridges and hills, which are characterised by steeper slopes, and the second-order streams are formed in the downstream direction, and so on.

The sub-basin I shows 10 streams and the sub-basin II shows 26 streams (Table 6.6). Thus, the entire watershed is having 36 streams. The watershed in both the sub-basins is characterised by relatively lower number of third-order streams and higher number of first-order and second-order streams, which constitute 90% and 88% of the total number of streams in the sub-basins I and sub-basin II, respectively.

The steeper the slopes, the higher the number of streams. Thus, higher number of first-order and second-order streams in the sub-basin II (Table 6.6) can be attributed to larger area of steeper slopes and associated with higher runoff, intense erosional processes, lower infiltration and lower permeability. In contrast to this, the proportion of area occupied by steeper slopes is comparatively very low in the sub-basin I, and hence, the smaller number of first-order and second-order streams. The lower number of third-order streams in both the sub-basins can be attributed to mature landscape, as they occur on plains.

(vii) Bifurcation ratio (Rb): It is an index of relief and dissection, which is defined as the ratio of a number of stream branches of a given order to a number of stream branches of next higher order [Horton, 1945; Eq. (6.2)].

$$Rb = \frac{Nu}{Nu+1} \tag{6.2}$$

where,

Nu = number of streams of a given order
$Nu + 1$ = number of streams of the next highest order

TABLE 6.7 Bifurcation Ratio (*Rb*)

Sub-basin	*Bifurcation ratio*			
	I/II	*II/III*	*III/IV*	*Average*
Sub-basin I	3.5	2.0	–	2.75
Sub-basin II	3.6	2.5	2.0	2.70

The bifurcation ratio (*Rb*) is an index of relief and dissection. According to Strahler (1964), it ranges from 3.0 to 5.0 for basins in which the geologic structures do not distort the drainage pattern, while a value of more than 5 indicates a structural control. If it is less than 3, it indicates the absence of structural control. A bifurcation ratio of less than 5, as a whole, reflects the geomorphological control over the development of drainage pattern.

The average bifurcation ratios for both the sub-basins are 2.75 and 2.70 (Table 6.7). The ratios between first-order and second-order streams are 3.5 and 3.6, while those for the other stream orders typically vary from 2.0 to 2.5. These ratios are explicable in terms of relief. The observed higher bifurcation ratios between first-order and second-order streams can be attributed to high relief and highly dissected nature of the terrain, where these streams originate. Further, the average bifurcation ratio is less than 3, which indicates the absence of structural control. Thus, the bifurcation ratio indicates the geomorphologic control in the development of the drainage of the watershed and the lack of structural control.

(viii) Stream length (Lu): It is the length of stream of a particular order of the drainage basin (Morisawa, 1957).

TABLE 6.8 Stream Lengths (*Lu*)

Sub-basin	*Stream lengths* (km)				
	I	*II*	*III*	*IV*	ΣLu
Sub-basin I	8.55	5.53	0.47	–	14.55
Sub-basin II	15.08	6.56	1.58	0.54	23.76

The length of stream reflects the hydrological properties of underlying rocks over an area of consecutive stream orders. The length of streams decreases with the increase in the stream orders, which is due to the preservation of geometrical similarity in the basin of increasing order (Strahler, 1964).

The total stream lengths in both the sub-basins are essentially contributed by the stream lengths of the first-order and second-order streams, which constitute 97% of the total stream length in the sub-basin I and 91% of the total stream length in the sub-basin II. The total stream length of the sub-basin II (23.76 km) is 1.63 times higher than the total stream length of sub-basin I (14.55 km; Table 6.8). This is explicable in terms of infiltration and permeability, which are lower in the sub-basin II, and hence, the higher stream lengths and vice versa in the case of sub-basin I.

(ix) Average stream length (La): It is the ratio of the length of the streams to a number of streams of the corresponding order of streams [Strahler, 1964; Eq. (6.3)], which is expressed in kilometres (km).

$$La = \frac{\Sigma Lu}{Nu} \tag{6.3}$$

where,

ΣLu = total length of the streams (km)

Nu = number of streams of the corresponding order of streams

TABLE 6.9 Average Stream Lengths (*La*)

Sub-basin	*Average stream lengths* (km)			
	I	*II*	*III*	*IV*
Sub-basin I	1.22	2.77	0.47	–

Sub-basin II	0.84	1.31	0.79	0.54

The average length of streams gives information about the length of the streams per number of streams. The differences in the average length of streams among the stream orders appear to be caused by the distribution of number of streams along with their lengths in the order of streams, according to the occurrence of surface rock permeability with respect to topography. It explains that the length of streams increases as the number of streams increases due to the development of drainage network caused by the topography and surface rock permeability.

A close examination of Table 6.9 reveals that the average stream lengths of the first-order and second-order streams in sub-basin I are significantly higher as compared to those of the sub-basin II. This is very important as the higher infiltration and higher permeability of the sub-basin I are expected to favour lower average stream lengths for the first-order and second-order streams. This deviation can be attributed to gentle slope, which forms a larger part of the sub-basin I, as the gentle slope/gradient causes branching of streams less effective and each stream joins the other stream at a greater distance. This is very evidently seen in the first-order streams defining the sub-parallel drainage pattern (see Figure 6.1). A visual inspection of Figure 6.1 reveals that these are the longest first-order streams in the entire catchment.

(x) Stream length ratio (Lr): It is the ratio of average length of streams of a given order to the average length of streams of the next lowest order within the drainage basin [Horton, 1945; Eq. (6.4)].

$$Lr = \frac{\Sigma Lu}{Lu - 1} \quad (6.4)$$

where,

ΣLu = average length of streams (km) of a given order
$Lu - 1$ = average length of streams of the next lowest order

TABLE 6.10 Stream Length Ratio (*Lr*)

Sub-basin	*Stream length ratio* (km)		
	II/I	*III/II*	*IV/III*
I	2.27	0.17	–
II	1.60	0.60	0.68

For understanding the relationship of discharge of surface flow in relation to erosional stage of a basin, the stream length ratio (*Lr*) evaluates the relative rock permeability in a basin. The stream length ratio of the second-order streams shows a high value of 2.27 compared to those in the third-order streams (0.17) in the sub-basin I, while it is noted as 1.60 in the second-order streams, 0.60 in the third-order streams and 0.68 in the fourth-order streams in the sub-basin II (Table 6.10). This means the stream length ratio is more than one in the second-order streams of both the sub-basins, while it is less than one in the third-order and fourth-order streams of the sub-basins. This difference is an index of the infiltration of recharge water. Accordingly, the second-order streams indicate that they flow through the rocks of high rock permeability in both the sub-basins, the third-order streams reflect that they run through the area of low permeability in the rock surfaces and the fourth-order streams infer that they flow where there is a medium rock permeability in the sub-basin II.

(xi) Length of overland flow (Lg): It is the length of overland flow which is equal to the half of the reciprocal of the drainage density [Horton, 1945; Eq. (6.5)]. It is expressed in square kilometre per kilometre (km^2/km).

$$Lg = \frac{1}{2D} \qquad (6.5)$$

where,

D = drainage density (km/km^2)

TABLE 6.11 Length of Overland Flow (*Lg*)

Sub-basin	*Length of overland flow* (km^2/km)
Sub-basin I	0.19
Sub-basin II	0.15

A length of overland flow is the length of stream flow paths projected on to the horizontal from a point of drainage divide to a point on the adjacent stream channel. It is one of the most important independent variables, affecting both the hydrological and physiographical development of the drainage basin. Thus, this is the length of water over the ground before it gets concentrated into definite stream channels. This factor relates inversely to the average slope of the channel and is quite synonymous with the length of sheet flow to a large degree. It is significantly affected by infiltration and percolation through the soil, both varying in time and space.

The values of the length of overland flow for the sub-basins I and sub-basin II are 0.19 and 0.15 km^2/km, respectively (Table 6.11). This means that the water has to travel more distance in the sub-basin I, as compared to the sub-basin II, before it gets concentrated into a definite stream channel, thereby reflecting the controls exerted by slope and infiltration.

(xii) Drainage density (D): It is the ratio of total length of streams of all orders per unit drainage area [Horton, 1945; Eq. (6.6)], which is expressed in kilometre per square kilometre (km/km^2).

$$D = \frac{\Sigma Lu}{a} \tag{6.6}$$

where,

ΣLu = total length of streams of all orders (km)
a = basin area (km^2)

TABLE 6.12 Drainage Density (*D*)

Sub-basin	*Drainage density* (km/km^2)
Sub-basin I	2.66
Sub-basin II	3.39

The drainage density reflects not only the closeness of spacing of streams but also the structural network of the underlying rocks of a watershed basin so that it is a significant index in determining the time travelled by water (Langbein, 1947). It depends on the climate, surface roughness and runoff. A low drainage density occurs in a region of high resistant or high permeable strata under dense vegetation and low relief, while a high drainage density results from a region of weak or impermeable rocks under sparse vegetation and mountainous relief (Strahler, 1964). On the other hand, the nature of surface area of a basin is permeable where the value of the drainage density is less than 5 km/km^2 (Smith, 1950; Strahler, 1957).

As the drainage density is a measure of landscape dissection and runoff potential, it is a result of interacting factors controlling the surface runoff and such factors for the watershed are exemplified by relief, total number of streams, total stream length and basin area. Thus, the high-drainage density basin is associated with a relatively rapid hydrological response to the rainfall events, while the low-drainage density basin is associated with a poorly drained basin with a slow hydrologic response.

The values of the drainage density for the sub-basins I (2.66 km/km^2) and sub-basin II (3.39 km/km^2; Table 6.12) indicate that the sub-basin II is comparatively more dissected with high runoff potential, while the sub-basin I is less dissected and has lower runoff potential. This inference is consistent with the observation on various relief parameters. Further, the drainage density of sub-basin II is 1.27 times higher than that of the sub-basin I and this indicates that sub-basin II is more permeable than sub-basin I.

(xiii) Stream frequency (F): It is the ratio of the total number of streams in a drainage basin to the area of the basin area [Horton, 1932; Eq. (6.7)].

$$F = \frac{\Sigma Nu}{a} \tag{6.7}$$

where,

ΣNu = total number of streams in a drainage basin

a = basin area (km^2)

TABLE 6.13 Stream Freuency (*F*)

Sub-basin	*Stream frequency* (per km^2)
Sub-basin I	1.83
Sub-basin II	3.71

A stream frequency or channel frequency or drainage frequency is a topographic texture. If the stream frequency is higher, it reflects a greater runoff due to steeper slope. The stream frequencies for the sub-basins I and sub-basin II are 1.83 and 3.71, respectively (Table 6.13). They indicate that the stream frequency in the sub-basin II is 2.03 times greater than that of the sub-basin I. The observed variations are explicable by low relief and higher surface rock permeability and infiltration in sub-basin I and vice-versa in the case of sub-basin II.

Tables 6.12 and 6.13 reveal that drainage density and stream frequency bear positive correlation, indicating that stream length increases with the increase in stream population. However, this correlation is not perfect, i.e. the increase in stream length is not in proportion with the increase in stream numbers. While the total number of streams (Table 6.6) in the sub-basin II (26) is 2.6 times more than that of the sub-basin I (10), the total stream length (Table 6.8) in the sub-basin II (23.76) is only 1.63 times higher than that of the sub-basin I (14.55). This is due to the development of fewer numbers of streams of longer stream lengths in sub-basin I and comparatively higher number of streams of shorter stream lengths in sub-basin II. This is collaborated by the average stream lengths of first-order and second-order streams, which (first-order and second-order streams) essentially contribute to the total stream lengths.

(xiv) Drainage texture (Dt): It is the product of drainage density and stream frequency [Smith, 1950; Eq. (6.8)].

$$Dt = D \times F \tag{6.8}$$

where,

D = drainage density (km/km^2)
F = stream frequency (per km^2)

TABLE 6.14 Drainage Texture (*Dt*)

Sub-basin	*Drainage texture*
Sub-basin I	4.86
Sub-basin II	12.57

The drainage texture (*Dt*) is a measure of closeness of channel spacing in a basin, which gives an idea of the infiltration characteristics of a basin. The drainage texture depends on the climate, rainfall, vegetation, soil and rock type, infiltration rate, relief and stage of development of an area.

A fine drainage texture indicating a low infiltration and high runoff results from soft or weak rocks unprotected by vegetation, while a coarse drainage texture is caused by high infiltration and low runoff and it reflects massive or resistant rocks. Sparse vegetation with an arid climate causes a finer drainage texture than the vegetation developed on similar rocks in a humid climate. According to Smith (1950), if the drainage texture is less than 4, it comes under a coarse drainage texture; if it is in between 4 and 10, it is classified as an intermediate drainage texture; if it varies from 10 to 15, it is considered as a fine drainage texture; and if it is more than 15, it is categorised as an ultra-fine drainage texture. It can also be categorised into very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8), and very fine (>8) for more clarity. Thus, the increasing drainage texture indicates the decreasing rate of infiltration due to steep slope and low rock permeability.

The values of the drainage texture of the sub-basins I and sub-basin II are 4.86 and 12.57, respectively (Table 6.14). As per the classification of the drainage texture, the sub-basin I comes under the intermediate drainage texture and the sub-basin II comes under the fine drainage texture. The drainage texture of the sub-basin II is 2.59 times higher than that of the sub-basin I and this indicates higher infiltration in the sub-basin I.

(xv) Drainage texture ratio (Dt_r): It is measure of the total number of streams of all orders per perimeter of that basin [Horton (1945; Eq. (6.9)].

$$Dt_r = \frac{Nu}{p} \tag{6.9}$$

where,

Nu = number of streams

P = perimeter (km)

TABLE 6.15 Drainage Texture Ratio (Dt_r)

Sub-basin	*Drainage texture*
Sub-basin I	0.85
Sub-basin II	2.03

The drainage texture ratio (Dt_r) is also an indicator for assessment of the rate of infiltration like drainage density and drainage texture. If the drainage texture ratio is high, the rate of infiltration is low and the rate of runoff is high.

The drainage texture ratio of the sub-basins I and sub-basin II are 0.85 and 2.03, respectively (Table 6.15). Thus, the drainage texture ratio is high in the sub-basin II and low in the sub-basin I, indicating that the rate of infiltration is high in the latter sub-basin due to high rock permeability than that in the former sub-basin I, where it is low because of low permeability of the rock surfaces.

Generally, the drainage texture of the sub-basin I (0.85) is very coarse, while it is coarse in the case of sub-basin II (2.03; Table 6.15). This difference can be visually seen in Figure 6.1, where the streams in the sub-basin II have comparatively wider spacing. The observed differences can be attributed to differences in infiltration and permeability of the two sub-basins.

(xvi) Constant of channel maintenance (C): It is the inverse of drainage

density [Schumm, 1956; Eq. (6.10)], which is expressed in square kilometre per kilometre (km^2/km).

$$C = \frac{1}{D} \tag{6.10}$$

where,

D = drainage density (km/km^2)

TABLE 6.16 Constant of Channel Maintenance (C)

Sub-basin	*Drainage texture* (km^2/km)
Sub-basin I	0.38
Sub-basin II	0.29

Information about the required surface area to maintain one kilometre of stream channel is expressed in terms of constant of channel maintenance (C). Generally, the higher the constant of channel maintenance of a basin, the greater is the permeability of the rocks of that basin.

The computed values of the constant of channel maintenance for sub-basins I and sub-basin II are 0.38 km^2/km and 0.29 km^2/km, respectively (Table 6.16). These reflect the low constant of channel maintenance. However, there is a difference in their values between the sub-basins. For example, the surface area of the sub-basin II is less than that of the sub-basin I, where it is high. Relatively, the surface area of 0.38 km^2/km in the sub-basin I and of 0.29 km^2/km in the sub-basin II is needed to sustain one kilometre of stream channel. This implies the occurrence of low rock permeability in the sub-basin II compared to that in the sub-basin I, where the permeability of the rock surfaces is high.

(xvii) Circulatory ratio (Rc): It is the ratio of basin area to the area of a circle, having the same perimeter as the basin [Miller, 1953; Eq. (6.11)].

$$Rc = \frac{4\pi a}{P^2} \tag{6.11}$$

where,

a = basin area (km^2)

P^2 = perimeter (km)

TABLE 6.17 Circulatory Ratio (Rc)

Sub-basin	*Circulatory ratio*

Sub-basin-I	0.49
Sub-basin-II	0.54

The circularity ratio (*Rc*) is a dimensionless ratio, reflecting the degree of circularity of a basin. It reflects a stage of dissection in any region and also an index of structural fabric of underlying rocks. If the circularity ratio is exactly one, the shape of the basin is set to become perfectly circular [Figure 6.6(a)], in which the runoff is in higher quantity.

The values of the circularity ratio for the sub-basin I and sub-basin II are 0.49 and 0.54, respectively (Table 6.17), indicating that these basins are not circular, but elongated; the sub-basin II is comparatively slightly more elongated (Figure 6.6).

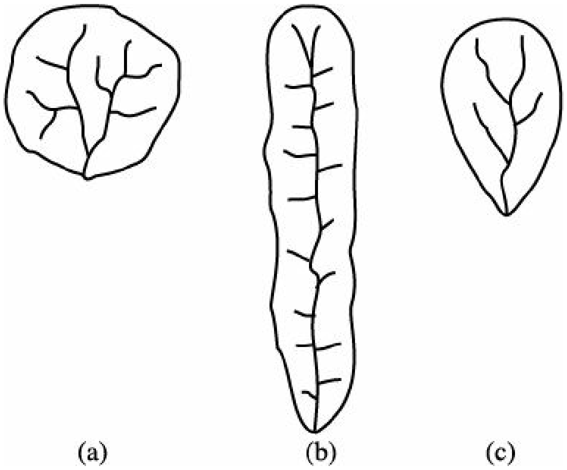


FIGURE 6.6 Shapes of the (a) circular, (b) elongated, and (c) normal basins.

(xviii) Elongation ratio (Re): It is the ratio of the diameter of a circle of the same area as the drainage basin to the maximum length of the basin [Schumm, 1956; Eq. (6.12)].

$$Re = \left(\frac{2}{l}\right)\left(\frac{a}{\pi}\right)^{0.5} \tag{6.12}$$

where,

I = basin length (km)

a = basin area (km^2)

TABLE 6.18 Elongation Ratio (*Re*)

Sub-basin	*Elongation ratio*
Sub-basin I	0.59
Sub-basin II	0.66

The elongation ratio (*Re*) is a significant index in the analysis of watershed shape, which helps in giving an idea about the hydrological character of drainage in a basin. The values of elongation ratio vary from 0.6 to 1.0 over a wide variety of climatic and geologic conditions (Strahler, 1964). Values close to 1.0 are typical of region of very low relief due to circular shape of the basin [Figure 6.6(a)], whereas values in the range of 0.6 to 0.8 are usually associated with high relief and steep ground slope because of elongated shape of the basin [Figure 6.6(b)]. However, the elongation ratio can also be grouped into three classes, namely, circular (>0.9), oval (0.9–0.8), and less elongated (<0.7).

The values of elongation ratios for the sub-basin I (0.59) and sub-basin II (0.66) indicate that both the sub-basin and are less elongated (Table 6.18), depending on the climate and geological conditions.

(xix) Form factor (Ff): It is the dimensionless ratio of the area of the basin to the square of the length of the basin [Horton, 1932; Eq. (6.13)].

$$Ff = \frac{a}{l^2} \tag{6.13}$$

where,

a = basin area (km^2)
l = basin length (km)

TABLE 6.19 Form Factor (*Ff*)

Sub-basin	*Form factor*
Sub-basin I	0.27
Sub-basin II	0.34

As the length of the basin increases, the peak runoff decreases. Thus, the form factor (*Ff*) shows an inverse relation with the length of the basin and a direct relation with the peak runoff. If the form factor is zero, it indicates that the shape of the basin is highly elongated, with flat peak flows for longer duration; if it is one, it shows a perfect circular shape of the basin [Figure 6.6(a)], with high peak flows for short duration (Horton, 1932). Elongated watershed with low form factor maintains flat peak flows for longer duration.

The values of the form factor, i.e., 0.27 and 0.34 for the sub-basin I and sub-basin II, respectively (Table 6.19) indicate that the shapes of the sub-basins are elongated; sub-basin I is comparatively slightly more elongated.

(xx) Relief (h): It is the difference between the maximum and minimum elevations in a basin (m) above mean sea level (amsl) (Strahler, 1964).

$$h = \text{Maximum elevation} - \text{Minimum elevation}$$

TABLE 6.20 Relief, *h* (m amsl)

Sub-basin	*Elevation*		*Relief*
	Maximum	*Minimum*	
Sub-basin I	200	50	150
Sub-basin II	305	45	260

The higher relief indicates the lesser infiltration and greater runoff due to lower surface rock permeability, and vice versa. The maximum and minimum elevations are 200 and 50 m amsl in the sub-basin I and 305 and 45 m amsl in the sub-basin II (Table 6.20). Thus, the relief of the sub-basin I is 150 m amsl and that of sub-basin II is 260 m amsl. This indicates that the relief of the sub-basin II is 1.73 times higher than the relief of the sub-basin I. The slope can be considered to be comparatively steeper in the sub-basin II, while in the sub-basin I, it can be considered to be gentle. This reflects comparatively less infiltration and higher runoff in the sub-basin II and vice versa in the case of sub-basin I.

(xxi) Relief ratio (Rr): It is the ratio of the maximum basin relief to the horizontal distance along the longest dimension of the basin parallel to the principal drainage line [Schumm, (1956; Eq. (6.14)].

$$Rr = \frac{h}{l} \tag{6.14}$$

where,

h = difference between the maximum and minimum elevations in a basin (m amsl)

l = basin length (km)

TABLE 6.21 Relief Ratio (*Rr*)

Sub-basin	*Relief ratio*
Sub-basin I	0.033
Sub-basin II	0.057

The relief ratio is a measure of the overall steepness of a drainage basin, which is an indicator of the intensity of erosion processes operating on the slope of a basin. The relief ratio of the sub-basin II (0.057) is 1.73 times higher than that of the sub-basin I (0.033; Table 6.21). These values indicate steeper slopes and higher intensity of erosion in the sub-basin II and vice versa in the case of sub-basin I.

(xxii) Relative relief (Rrf): It is the ratio of the maximum basin relief to the length of the boundary of the basin (perimeter; Melton, 1957; Eq. 6.15).

$$Rrf = h \times \frac{100}{p} \tag{6.15}$$

where,

h = difference between the maximum and minimum elevations in a basin (m amsl)

p = perimeter (km)

TABLE 6.22 Relative Relief (*Rrf*)

Sub-basin	*Relative relief*
Sub-basin I	1.27
Sub-basin II	2.03

The relative relief is also an index of rock permeability like the relief ratio. The higher the relative relief, the greater is the steep slope and the lower is the permeability of the rock surfaces. The values of the relative relief for the sub-basins I (1.27) and sub-basin II (2.03; Table 6.22) indicate steeper slopes and lower permeability in the sub-basin II, and gentle slopes and higher permeability in the case of sub-basin I. Thus, there is higher runoff and lower infiltration in the sub-basin II than those in the sub-basin I.

(xxiii) Ruggedness number (Rn): It is the product of maximum basin relief and drainage density within the drainage basin, which is a simple flow accumulation related index [Strahler, 1958; Eq. (6.16)].

$$Rn = h \times D \tag{6.16}$$

where,

h = difference between the maximum and minimum elevations in a basin (m amsl)

D = drainage density (km/km^2)

TABLE 6.23 Ruggedness Number (*Rn*)

Sub-basin	*Ruggedness number*

Sub-basin I	0.40
Sub-basin II	0.88

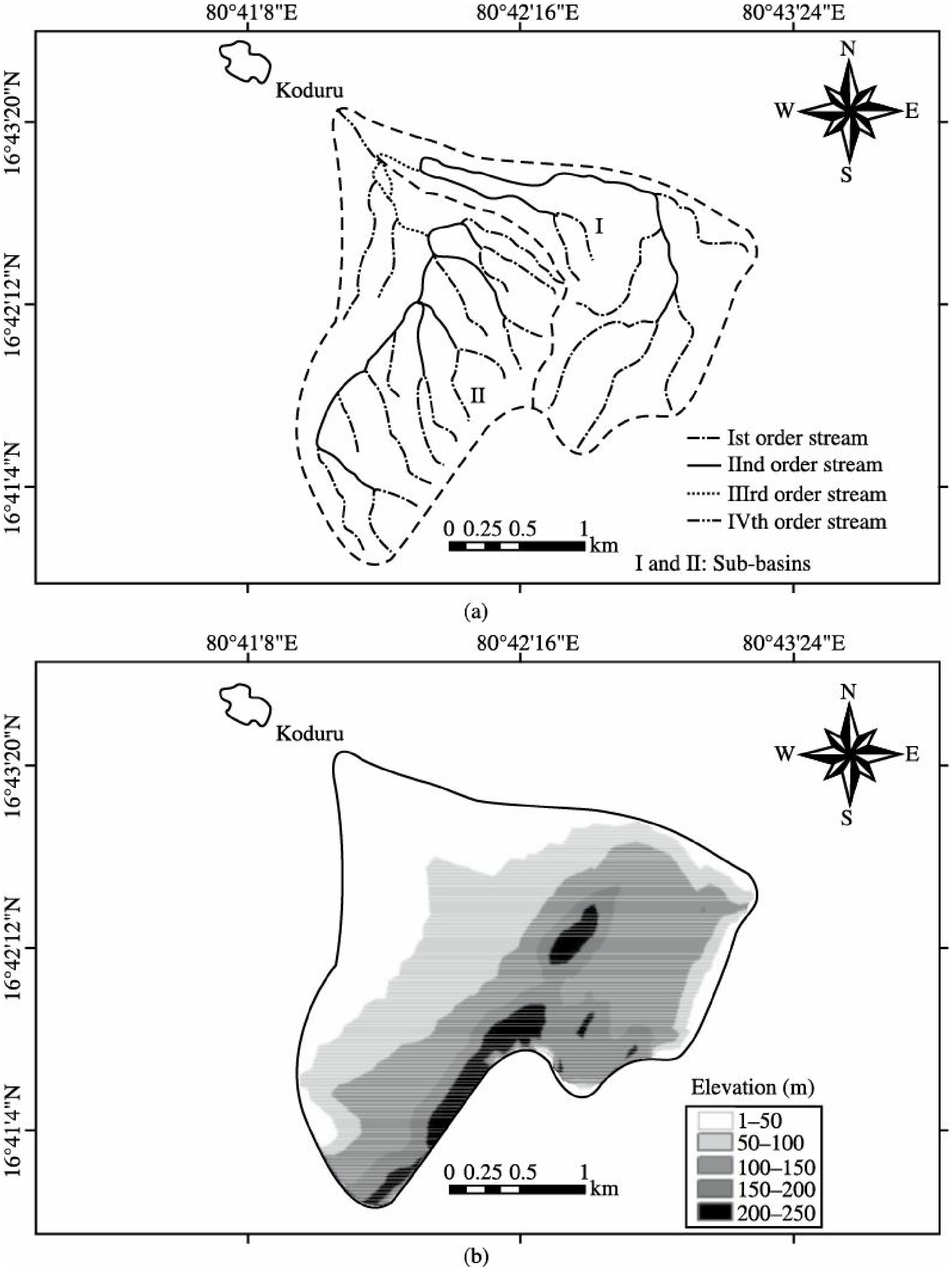
The ruggedness number (*Rn*) is a dimensionless component, which is a combination quality of slope steepness and length (Strahler, 1958). If both the variables (relief and drainage density) are large, extremely high values of the ruggedness number occur. The higher ruggedness number reflects the high basin relief, steep slopes, less resistant rocks and high rainfall, and the inverse is true in the case of lower ruggedness numbers.

The ruggedness number of the sub-basin II (0.88) is 2.2 times higher than that of the sub-basin I (0.40; Table 6.23), indicating high relief and steep slopes. Thus, the observed differences in relief and steepness of the slopes in both the sub-basins are in agreement with the values of ruggedness numbers.

PROBLEM 7 A watershed is a pediplain with residual hills, occurring in the form of ridges, where many first-order streams originate. Loamy soils are the dominant type of soils, with a very fine grain. The basin area is underlain by the gneissic rocks of the Eastern Ghats with a foliation of northeast-southwest (NE-SW) and dips 45^{o} to 50^{o} southeast (SE). The average bifurcation ratio is less than 3. Compare the drainage pattern (see Figure 7.1) with digital elevation model (DEM) of the basin and explain the geological controlling factors of the basin and the slope characteristics with respect to infiltration and runoff.

Key Concept The nature of drainage pattern depends on a number of factors like topography, soil type, bedrock type, climate and vegetation cover. A digital elevation model (DEM) is a digital model or three-dimensional (3D) representation of a terrain's surface created from a terrain elevation data. Comparison of the drainage pattern with DEM explains the controlling factors of the basin and the slope characteristics with respect to infiltration and runoff, which play a vital role for the development of water resources.

Data of the given problem



(a)

(b)

FIGURE 7.1 (a) Drainage pattern and (b) digital elevation model (DEM).

Solution

The overall drainage pattern of the watershed is sub-dendritic, with a patch of sub-parallel drainage pattern in the southern part of sub-basin I [Figure 7.1(a)]. The flow direction of the streams mimics the slope of the basins. The sub-parallel drainage pattern indicates the control exerted by gradient and lack of structural interference. The absence of structural control on the watershed is also evidenced by bifurcation ratio, which is less than 3 (Table 6.7). Lithology and soil cover are not expected to show much variations in the watershed, as dendritic drainage pattern indicates homogenous and uniform soil and rocks.

The digital elevation model (DEM) [Figure 7.1(b)] indicates that the highest elevation in the micro-watershed trends north northeast-south southwest (NNE-SSW), forming a continuous strip along the south-eastern border of the sub-basin II, and occurring as a small patch approximately in the centre of the sub-basin I. The relief in the watershed is manifested by hill ridge in the sub-basin II and small isolated hills in the sub-basin I. The relief of the sub-basin II decreases towards the northwest (NW) direction. This indicates the steeper slope of the basin. In contrast to this, the sub-basin I slopes in northeast (NE) direction and then follows the NW direction. The slopes can be considered to be comparatively steeper in the sub-basin II.

On the other hand, the slope in the sub-basin I can be considered to be gentle, except a small patch around the hill, where the slopes are steeper. Thus, the sub-basin I is largely made of low-relief area with gentle slopes, whereas the sub-basin II is largely made of high-relief area with steeper slopes. Generally, the higher the relief, the lesser is the infiltration and the greater is the runoff. This reflects comparatively less infiltration and higher runoff in the sub-basin II and vice versa in the case of sub-basin I. The observed differences in the slopes are also collaborated by other parameters of relief.

PROBLEM 8 Find out the areas which are suitable for augmentation of surface water and groundwater resources, taking the explained drainage characteristics (in Problem 6) into account.

Key Concept Evolution of the drainage characteristics plays a significant role in the development of water resources. From this analysis, it can be possible to delineate the areas, which are suitable for augmentation of surface water storage as well as for groundwater recharge.

Data of the given problem

Morphometric characteristics presented in Tables 6.1 to 6.23 are taken into consideration here to explain the areas, which are suitable for augmentation of surface water and groundwater resources.

Solution

The various drainage characteristics explained in Tables 6.1 to 6.23 in the previous section (Problem 6) reveal that the watershed has homogenous and uniform cover of soil and rocks, and that the geomorphology (slope, permeability, etc. of the landforms), climate (rainfall) and geomorphic (fluvial) processes have exerted dominant controls over the development of drainage. Hence, it is possible to delineate the areas for augmenting the surface water and sub-surface water resources based on the results obtained from the morphometric analysis.

Infiltration capacity and permeability of watershed are the two important aspects that play key role in the development of groundwater resources. These two aspects are well-documented by drainage density, stream frequency, infiltration number and drainage texture in the watershed. Lower values of these parameters are expected to promote infiltration and permeation of water, and hence, point out areas favourable for augmenting the sub-surface water. The sub-basin I has comparatively lower values for these parameters (Tables 6.12 to 6.15), and hence, better suited, except the hilly areas, for augmenting the groundwater resources of the watershed. Within this basin, the area sloping towards NE (gently sloping) is more favourable, as groundwater movement in this area is expected to be slow, and hence, the groundwater is available for a longer period.

In the case of sub-basin II, the values of drainage density, stream frequency, infiltration number and drainage texture (Tables 6.12 to 6.15) are comparatively higher, and hence, do not favour the groundwater recharge. However, the plain areas occupied by third-order streams in the sub-basin II are considered to be important, as they are expected to have higher capacity of infiltration and higher permeability as compared to the sites of first-order and second-order streams. This is evidenced by rather low average stream length for the third-order streams (0.79 km) in comparison with higher average length of streams for the first-order (0.84 km) and second-order (1.31 km) (Table 6.9).

The augmentation of surface water resources essentially depends on the amount of surface water present in the catchment and its loss to groundwater. The latter is controlled by infiltration capacity and permeability of the catchment area and they are well-documented by drainage density, stream frequency, infiltration number and drainage texture (Tables 6.12 to 6.15). From the discussion on various morphometric parameters, it can be considered that basin area, total stream number, and total stream length are the three morphometric parameters, which reflect the quantity of surface present in the sub-basins. The higher values for the basin area, total stream number, total stream length, drainage density, stream frequency, infiltration number and drainage texture (Tables 6.3, 6.8 and 6.12 to 6.15) indicate that sub-basin II contains higher quantity of surface water as compared to sub-basin I. Within this basin, the areas of first-order and second-order streams are of prime importance, as they are associated with lower infiltration and lower permeability, and the surface run-off is high. Further, such areas occupy larger part of the sub-basin II.

Water is surplus in the watershed from July to November due to the absence of structural control over the basin. It can be inferred that most of the surplus water of the watershed is contributed by sub-basin II, as it contains higher quantity of surface water. In case of extreme rainfall events, there is scope for flooding, as it is observed that potential for flooding is positively correlated with drainage area, drainage density and ruggedness number (Tables 6.3, 6.12 and 6.23), and the values of these parameters are comparatively high for sub-basin II. Hence, to make optimum use of water resources of the watershed, it is suggested to divert the surplus water of the sub-basin II to sub-basin I, where it can be used to enhance the surface and/or sub-surface water resources of the sub-basin I. Thus, the diversion of surface water not only enhances water resources of sub-basin I but also reduces the possibility of flood hazards (if any) in the sub-basin II.

PROBLEM 9 A drainage basin has a minimum altitude of 75 m and a maximum altitude of 250 m amsl. The area between the consequent contours is presented in

Table 9.1. (a) draw the hypsometric curve and (b) estimate the hypsometric integral.

Key Concept Hypsometric analysis explains the overall slope and the forms of drainage basin, which is an important tool to assess and compare the geomorphic evolution of various landforms. It is expressed in terms of (a) hypsometric curve (HC) and (b) hypsometric integral (Hi). The HC is widely used directly to compare different watersheds and indirectly to assess their distribution in the area relative to relief, while the Hi is an indication of the cycle of the erosion, which is the total time required for reduction of land area to the base level. The higher the slope, the greater is the runoff and the lower is the infiltration. This supports the limited groundwater recharge.

Data of the given problem

Minimum altitude of the basin = 75 m amsl

Maximum altitude of the basin = 225 m amsl

Area between the consequent contours is shown in Table 9.1.

TABLE 9.1 Contour Elevations and Their Consequent Area

Contour elevations (m)	*Area between contours* (km^2)
75–100	0.440
100–125	0.414
125–150	0.330
150–175	0.189
175–200	0.066
200–225	0.031
225–250	0.012

Solution

(a) Hypsometric curve (HC): Hypsometric curve is an empirical cumulative distribution function of elevations in a catchment. Calculation of the relative area and relative height of the drainage basin is shown in Table 9.2.

TABLE 9.2 Relative Area and Relative Height

Contour elevations	*Area between*	*Relative area [area between*	*h [lowest elevation in each contour – lowest elevation (75*	*Relative height [h/H = in which H is elevation difference between*

(m)	*contours, a* (km^2)	*contours/highest area between contours or a/A]*	*m) in contour elevations]*	*highest and lowest (250 –75 = 175 m)]*
75–100	0.440 (*A*)	0.440/0.440 = 1.00	75 – 75 = 0	0/175 = 0.00
100–125	0.414	0.414/0.440 = 0.94	100 – 75 = 25	25/175 = 0.14
125–150	0.330	0.330/0.440 = 0.75	125 – 75 = 50	50/175 = 0.29
150–175	0.189	0.189/0.440 = 0.42	150 – 75 = 75	75/175 = 0.43
175–200	0.066	0.066/0.440 = 0.15	175 – 75 = 100	100/175 = 0.57
200–225	0.031	0.031/0.440 = 0.07	200 – 75 = 125	125/175 = 0.71
225–250	0.012	0.024/0.440 = 0.03	225 – 75 = 150	150/175 = 0.86

A hypsometric curve is shown graphically as an *x*-*y* plot with relative area (*a*/*A*) on *x*-axis and the corresponding relative height on *y*-axis in a simple arithmetic graph (Figure 9.1).

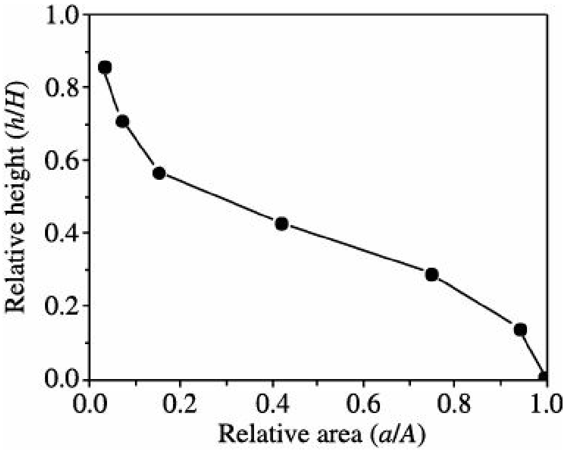


FIGURE 9.1 Hypsometric curve.

The first half of the HC indicates a concave form, which lies at comparatively low relief, where the area is associated with dissected and eroded landscape, while the rest of the HC curve indicates a convex form, which lies at comparatively high relief, where the area is associated with deeply incised, narrow valleys and broad upland area (see Appendix III). Thus, the basin shows a mature stage. Further, the S-shaped HC (Figure 9.1) suggests a relatively stable, but still developing landscape.

(**b) Hypsometric integral (Hi):** It is a dimensionless number that allows different basins to be compared regardless of scale to rank the basins in terms of this type of activity.

$$\text{Hi} = \frac{\text{Mean elevation} - \text{Minimum elevation}}{\text{Maximum elevation} - \text{Minimum elevation}} \tag{9.1}$$

Therefore, $$\text{Hi} = \frac{(250 - 75) - 75}{250 - 75} = 0.57$$

The Hi is an indication of the cycle of the erosion. The cycle of the erosion is the total time required for reduction of land area to the base level (Appendix III). Here, the value of Hi is 0.57. It indicates an ‘equilibrium or mature stage’ and is dominated by diffusive processes (mainly hill slope processes).

PROBLEM 10 The contour elevations vary from 100 m (downstream side) to 600 m (upstream side) in a basin. The contour interval is 100 m. The contour intersections by vertical lines are 70 and by horizontal lines are 120. The total length of the vertical grid segments is 49,000 m and of the horizontal grid segments is 51,600 m. Compute the mean slope of the basin.

Key Concept An average slope of the basin or watershed is the product of the slope of the vertical and horizontal directions, which offers information about the watershed topography. It is considered as an independent variable. The average slope of a watershed influences the value of the time of concentration radically and the runoff generated by a rainfall directly. The lower the topography, the lower is the runoff and the greater is the infiltration. This supports the higher groundwater recharge.

Data of the given problem

Contour elevations of the basin = 100 to 600 m
Contour interval = 100 m
Contour intersections by vertical lines = 70
Contour intersections by horizontal lines = 120
Total length of the vertical grid segments = 49,000 m
Total length of the horizontal grid segments = 51,600 m

Solution

The contour map of the basin is sub-divided into a number of square grids of equal size by drawing vertical and horizontal lines to compute the slope of the basin (Figure 10.1).

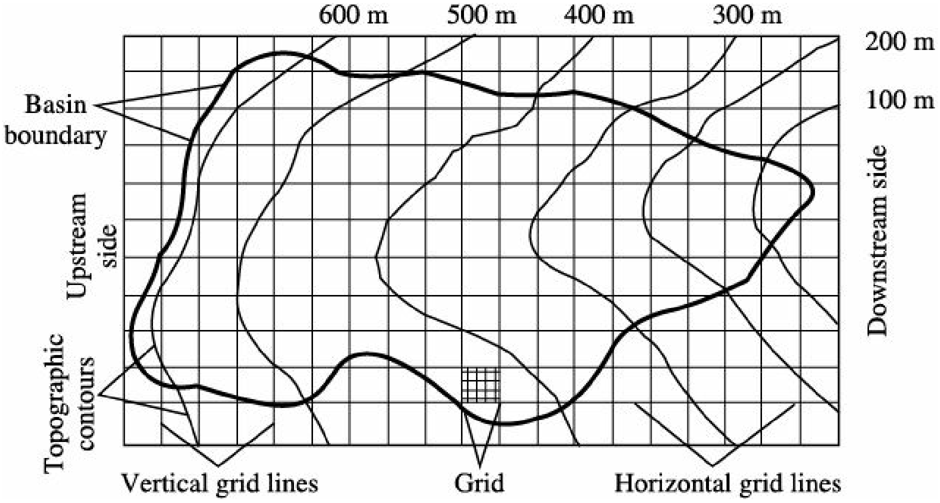


FIGURE 10.1 Contour elevations, vertical and horizontal grids and their intersections in a basin.

Mean slope of the basin (*S*): It is the ratio of the number of contour intersections by vertical and horizontal lines to the total length of the concerned grid segment [Eq. (10.1)] which is expressed in metre per metre (m/m) or percentage (%).

$$S = \frac{N_c \times C_l}{\Sigma Y} \tag{10.1}$$

where,

N_c = number of contour intersections by vertical lines

C_l = number of contour intersections by horizontal lines

$\sum Y$ = total length of the concerned direction grid segments (m)

(a) In vertical direction $(S_y) = \dfrac{N_c \times C_l}{\Sigma Y}$ (10.2)

Therefore, $S_y = \dfrac{70 \times 100}{40{,}000} = 0.1429$ m/m

(b) In horizontal direction $(S_x) = \dfrac{N_c \times C_l}{\Sigma Y}$ (10.3)

Therefore, $S_x = \dfrac{120 \times 100}{51{,}600} = 0.2326$ m/m

Therefore, mean slope of the basin $(S) = \dfrac{S_y \times S_x}{2}$ (10.4)

$$S = \frac{0.1429 + 0.2326}{2} = 0.1878 \text{ m/m or } 18.78\%$$

(c) *Horton's formula (1938):* It is the ratio of the number of contour intersections by horizontal and vertical lines to the total length of both the vertical and horizontal grid segments
[Eq. (10.5)], which is expressed in percentage (%).

$$\text{Mean slope of the basin } (S) = \frac{1.5(C_l) \times N_c}{\Sigma L} \tag{10.5}$$

where,

C_l = number of contour intersections by horizontal lines

N_c = number of contour intersections by vertical lines

$\sum L$ = total length of both the vertical and horizontal grid segments (m)

Therefore, $S = \dfrac{1.5 \times 100(70 + 120)}{(49{,}000 + 51{,}600)} = 0.2833$ or 28.33%

3

Hydrological Properties

PROBLEM 11 Calculate the cumulative of the grain size from the mechanical analysis of the soil sample (Table 11.1) and draw the grading curve. Classify the soil type, following the Indian Standard Institution (ISI) grain size scale, and determine the (a) effective grain size, (b) 3rd quartile, (c) median grain size, (d) screen grain size, (e) 1st quartile, (f) uniformity coefficient, (g) sorting coefficient, and (h) range of size. Also, explain their importance in the groundwater studies.

Key Concept Grain size analysis test is performed to determine the percentage of different grain sizes contained within a soil. First, record the weight of the dry soil sample. Second, obtain the mass of soil retained on each sieve by subtracting the weight of the empty sieve from the mass of the sieve + retained soil, and record this mass as the weight retained. The sum of these retained masses should be approximately equals the initial mass of the soil sample. Calculate the percent retained on each sieve by dividing the weight retained on each sieve by the original sample mass. Calculate the percent passing (or percent finer) by starting with 100 percent and subtracting the percent retained on each sieve as a cumulative procedure. The grain size analysis provides information about the porosity and infiltration characteristics of the soils, which are the important parameters to assess the possible conditions of the occurrence of groundwater.

Data of the given problem

TABLE 11.1 Mechanical Analysis of the Soil Sample

ISI sieve aperture dimension, D (mm)	*Weight retained* (g)
2.80	56.9
2.00	128.9
1.40	93.1
1.00	55.6

0.71	47.7
Bottom pan	48.8
Total	431.0

Solution

Calculation of cumulative grain size: Calculation of this procedure is shown in Table 11.2, taking the data from Table 11.1.

TABLE 11.2 Results of Mechanical Analysis of the Sample

ISI sieve aperture dimension, D (mm)	*Weight retained* (g)	*Cumulative of weight retained*	*Cumulative % retained*	*Cumulative % passing, p*
(a)	*(b)*	*(c)*	*(d = b ×* 100/*Total b)*	*(e =* 100 *– d)*
2.80	56.9	56.9	13.2	86.8
2.00	128.9	185.8	43.1	56.9
1.40	93.1	278.9	64.7	35.3
1.00	55.6	334.5	77.6	22.4
0.71	47.7	382.2	88.7	11.3
Bottom pan	48.8	431.0	100.0	0
Total	431.0			

Grading curve: A grading curve is drawn on a semi-logarithmic graph (Figure 11.1), taking the values of the sieve aperture dimension (*D*) on *x*-axis and cumulative % passing (*p*) on *y*-axis for determination of grain size, effective grain size, quartile, median, screen size, sorting coefficient, uniformity coefficient and range of size of the sample.

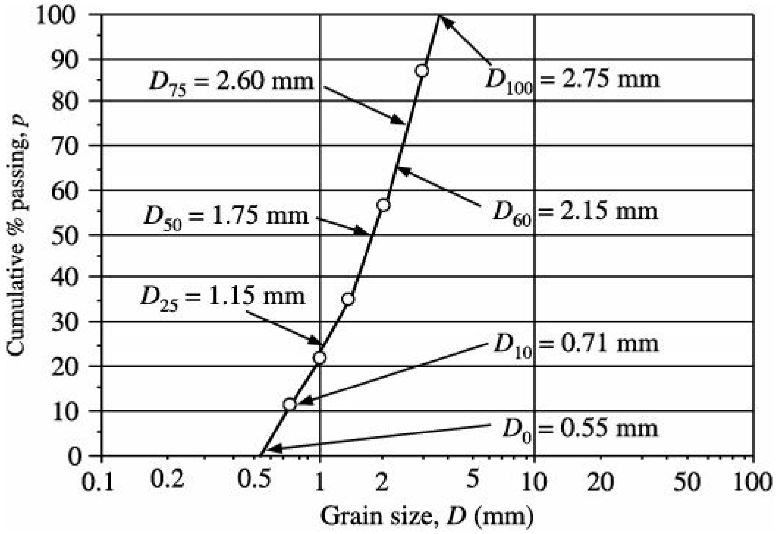


FIGURE 11.1 Grading curve.

Classification of soil type (ISI): The soil is classified as coarse sand material because the grain size of the aquifer material passes through sieve aperture dimensions of 0.71 mm to 2.80 mm (Table 11.2). Thus, it has a good infiltration capacity.

$$\text{Grain size } (D_0) = 0.55 \text{ mm}$$

The observed value of grain size D_0 is 0.55 mm (Figure 11.1), indicating a medium sand (Table 11.3), which shows a moderate porosity so that it has a moderate infiltration capacity.

$$\text{Grain size } (D_{100}) = 2.75 \text{ mm}$$

From Figure 11.1, the observed grain size D_{100} is 2.75 mm, which shows a gravel material (Table 11.3), reflecting a very good porosity and infiltration.

a. Effective grain size (D_{10}) = 0.71 mm

   The observed value of the effective grain size is 0.71 mm (Figure 11.1), which shows coarse sand (Table 11.3). The effective grain size is an index of fineness of the material, which corresponds to 10% of the material being finer and 90% coarser. Thus, the coarse sand indicates a good porosity and higher rate of infiltration.

b. 3rd quartile (D_{25}) = 1.15 mm

   From Figure 11.1, the observed 3rd quartile is 1.15 mm, which comes under coarse sand (Table 11.3). But, the 3rd quartile corresponds to 25% of the material being finer and 75% coarser so that it has relatively good porosity and good infiltration.

c. Median grain size (D_{50}) = 1.75 mm

The observed median grain size value is 1.75 mm (Figure 11.1), which shows coarse sand (Table 11.3). But, the median grain size corresponds to 50% of the material being finer and 50% coarser. Therefore, it indicates a medium porosity and moderate infiltration.

d. Screen grain size (D_{60}) = 2.15 mm

As per Figure 11.1, the observed value of screen grain size is 2.15 mm, which comes under a gravel category (Table 11.3). However, the screen grain size corresponds to 60% of the material being finer and 40% coarser. Therefore, this soil has poor porosity as well as poor infiltration.

e. 1st quartile (D_{75}) = 2.60 mm

The observed grain size of 1st quartile is 2.60 mm (Figure 11.1), indicating a gravel type (Table 11.3). But, the 1st quartile corresponds to 75% of the material being finer and 25% coarser so that it shows a very poor porosity and also a very low infiltration.

f. *Uniformity coefficient* (C_u) is an index of grading or particle size distribution of the soil material. It is expressed as the ratio of the screen grain size (D_{60}) to the effective grain size (D_{10}).

$$C_u = \frac{D_{60}}{D_{10}} \tag{11.1}$$

$$C_u = \frac{2.15}{0.71} = 3.03$$

Lower C_u (< 2.0) indicates a more uniform or poor grading material, while higher C_u (>2.0) indicates a well-graded or non-uniform material. Thus, C_u (=3.03) of the soil represents a non-uniform material. A uniform graded material has a higher porosity than a less uniform graded material. Therefore, it also indicates a higher infiltration.

g. The *sorting coefficient* (S_0) reflects the variation in the grain sizes that make up sediment, and it is defined as the ratio of the first quartile (D_{75}) to the third quartile (D_{25}).

$$S_0 = \sqrt{\frac{D_{75}}{D_{25}}} \qquad (11.2)$$

$$= \sqrt{\frac{2.60}{1.15}} = 1.50$$

This value of the sorting coefficient reflects the variation in the grain sizes of sediment. The larger the sorting coefficient, the greater is the range of grain sizes of the sediment. The sediment, which has a small range of grain sizes, is said to be *well-sorted*, whereas the sediment, which shows a wide range of grain sizes, is said to be *poorly-sorted*. Well-sorted sediment deposit has high porosity, while the poor-sorted sediment deposit has low porosity.

h. The *range of size* (C_r) is an index of effective distribution of grain size of the material, which is defined on the basis of the mean slope of the grain size curve. It is the ratio of the grain size of D_{100} to the grain size of D_0.

$$C_r = 2\log_{10}\frac{D_{100}}{D_0} \qquad (11.3)$$

$$C_r = 2\log_{10}\frac{2.75}{0.55} = 1.40$$

The observed value of the range of size is 1.40. The wider the range in size, the lower is the porosity. Thus, the rate of infiltration is low.

TABLE 11.3 Classification of Soils (Indian Standards Institution, 1970)

Material		*Grain size, D* (mm)
Gravel		> 2.0
Sand	Coarse	2.0 to 0.6
	Medium	0.6 to 0.2
	Fine	0.2 to 0.06
Silt	Coarse	0.06 to 0.02
	Medium	0.02 to 0.006
	Fine	0.006 to 0.002
Clay		< 0.002

PROBLEM 12 An undisturbed core sample of the sand material has 16 cm height and 4 cm inside diameter. The weight of the sample is 430 g before drying and 380 g after drying. The specific gravity of the sand is 2.65 g/cm^3. Compute the (a) water content, (b) volumetric water content, (c) porosity, (d) void ratio, (e) saturation percentage and (f) bulk density.

Key Concept The examination of the undisturbed core sample, before and after drying, depicts the aquifer material characteristics like water content, volumetric water content, porosity, void ratio, saturation percentage and bulk density, which are related to the hydrological properties.

Data of the given problem

Weight of the sand material before drying = 430 g

Weight of the sand material after drying = 380 g

Height of the core of the sand material = 16 cm

Diameter of the core of the sand material = 4 cm

Specific gravity of the sand = 2.65 g/cm^3

(a) Water content (W_c): It is the amount of water in a soil or porous material, which is the ratio of the water content before and after drying the sample [Eq. (12.1)] and is expressed in percentage (%).

$$W_c = \frac{W_w - W_d}{W_d} \times 100 \tag{12.1}$$

where,

W_w = weight of the sand material before drying (g)

W_d = weight of the sand material after drying (g)

Therefore, $$W_c = \frac{430 - 380}{380} \times 100 = 13.16\%$$

(b) Volumetric water content (V_w): It is the volume of water per unit volume of soil, which is defined as the ratio of difference of water before and after drying to volume of the substance [Eq. (12.2)]. This gives V_W as a volume fraction.

$$V_w = \frac{W_w - W_d}{V_c} \tag{12.2}$$

where,

V_c = volume of the core ($\pi r^2 H$)

Here, r = radius of the core $\left[\left(\frac{d}{2}\right) = \frac{4}{2} = 2 \text{ cm}\right]$

So, $\pi r^2 H = \frac{22}{7} \times 2^2 \times 16 = 200.96$

Therefore, $V_w = \frac{430 - 380}{200.96} = 0.25$

(c) Porosity (*n*): It is the measure of the void spaces in a substance, which is defined as the ratio of the volume of pore spaces to the total volume of the solid substance [Eq. (12.3)].

$$n = \frac{V_v}{V_c} \times 100 \tag{12.3}$$

where,

V_v = volume of the voids ($V_c - V_s$)

Here, V_s = volume of the solid $\left[\left(\frac{W_d}{S_s}\right) = \frac{380}{2.65} = 143.40\right]$

S_s = specific gravity of the sand (g/cm^3)

Then, $V_v = 200.96 - 143.40 = 57.56$

Therefore, $n = \frac{57.56}{200.96} \times 100 = 28.64\%$ or 0.29

(d) Void ratio (*e*): It is the count of pore volume of the substance, which is the ratio of the volume of void space (V_v) to the total volume of solid substance [V_s; Eq. (12.4)]

$$e = \frac{V_v}{V_s} \tag{12.4}$$

Therefore, $e = \frac{57.56}{143.40} = 0.40$

(e) Saturation percentage (S_p): It is the percentage (%) of the pore space that is occupied by water, which is defined as the ratio of the volumetric water content (V_w) to the porosity of the material [n; Eq. (12.5)]

$$S_p = \frac{V_w}{n} \times 100 \tag{12.5}$$

Therefore, $$S_p = \frac{0.25}{0.29} \times 100 = 86.21\%$$

(f) Bulk density (ρ_d): It is the density of the total soil or rock material, solids and voids after drying. This is the ratio of the dry weight of the substance (W_d) to the volume of the substance [V_c; Eq. 12.6)], which is expressed in gram per cubic centimetre (g/cm^3).

$$\rho_d = \frac{W_d}{V_c} \tag{12.6}$$

Therefore, $$\rho_d = \frac{380}{200.96} = 1.89 \text{ g/cm}^3$$

PROBLEM 13 A tracer is introduced into a well located at a distance of 65 m from a pumping well discharging at a constant rate of 125 m^3/h (Figure 13.1). Thickness of the aquifer is 45 m. A peak period of tracer concentration is observed for 30 days after injection. Estimate the effective porosity of the aquifer.

Key Concept Tracers are used to investigate sources, flow paths, flow processes and residence times of the groundwater. They are of two types—(a) natural (stable isotopes of water tritium) and (b) artificial (radioactive: bromide-82; activated: Indium; salts: NaCl; fluorescent dyes: Uranine; and drift particles: Lycopodium) substances that can be detected at low concentration. They can be assigned to a source or input function, and hence, that can be used to trace water flow or to identify water sources.

Data of the given problem

Distance between injection well and pumping well = 65 m

Pumping rate = 125 m^3/h or 500 m^3/day

Aquifer thickness = 45 m

Observation of tracer concentration in days = 30

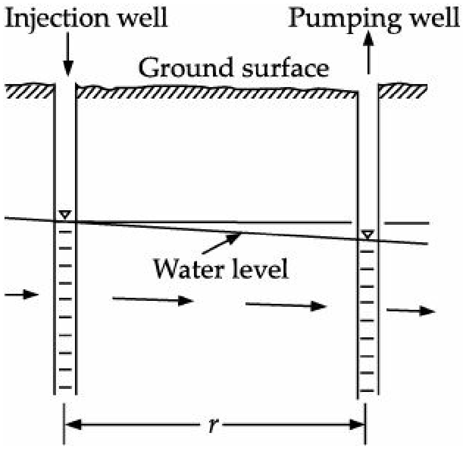


FIGURE 13.1 Introduction of tracer into a well.

Solution

Effective porosity (φ): It is define as a portion of the total void space of a porous material that is capable of transmitting a fluid, and it is the ratio of the volume of water pumped during travel time of water to the thickness of an aquifer [Eq. (13.1)].

$$\phi = \frac{V - V_d}{\pi r^2 b} \quad \text{or} \quad \frac{Qt}{\pi r^2 b} \tag{13.1}$$

where,

V = volume of water pumped during travel time of tracer (Q)
V_d = volume of water in involved part of depression cone (days)
t = observation of tracer concentration (days)
r = distance between injection well and pumping well (m)
b = thickness of the aquifer (m)

Therefore, $$\phi = \frac{500 \times 30}{3.14 \times 65 \times 65 \times 45} = 0.025$$

PROBLEM 14

a. Determine the capillary rise in soil, if the effective grain size and void ratio of the soil are 0.05 mm and 0.75, respectively.
b. Assume the possible type of soil according to the rise of capillarity.

Key Concept Groundwater occurs vertically in the sub-surface into two zones—(a) unsaturated zone and (b) saturated zone (Figure 14.1). The unsaturated zone may be divided into three sub-zones. They are soil-water zone, intermediate zone and capillary zone. The soil-water zone extends from the ground surface down through the major root zone. The water held in this zone is referred to as *soil moisture*. Intermediate zone occurs between the soil-water zone and the capillary zone. Capillary zone, also called *capillary fringe*, lies immediately above the saturated zone to the limit of capillary rise of water. The water, which is drawn up from the zone of saturation, held or stored against the force of gravity in the pore spaces of soil or rock is termed as *capillary fringe*. The water contained in the fringe is referred to as *capillary water*, which can move in all directions by capillary action. The capillary fringe is higher in fine-grained soils (clays) than in coarse-grained ones (gravels) because of the greater tensions created by the smaller pore spaces. Thus, the higher the grain size, the lower is the capillary rise.

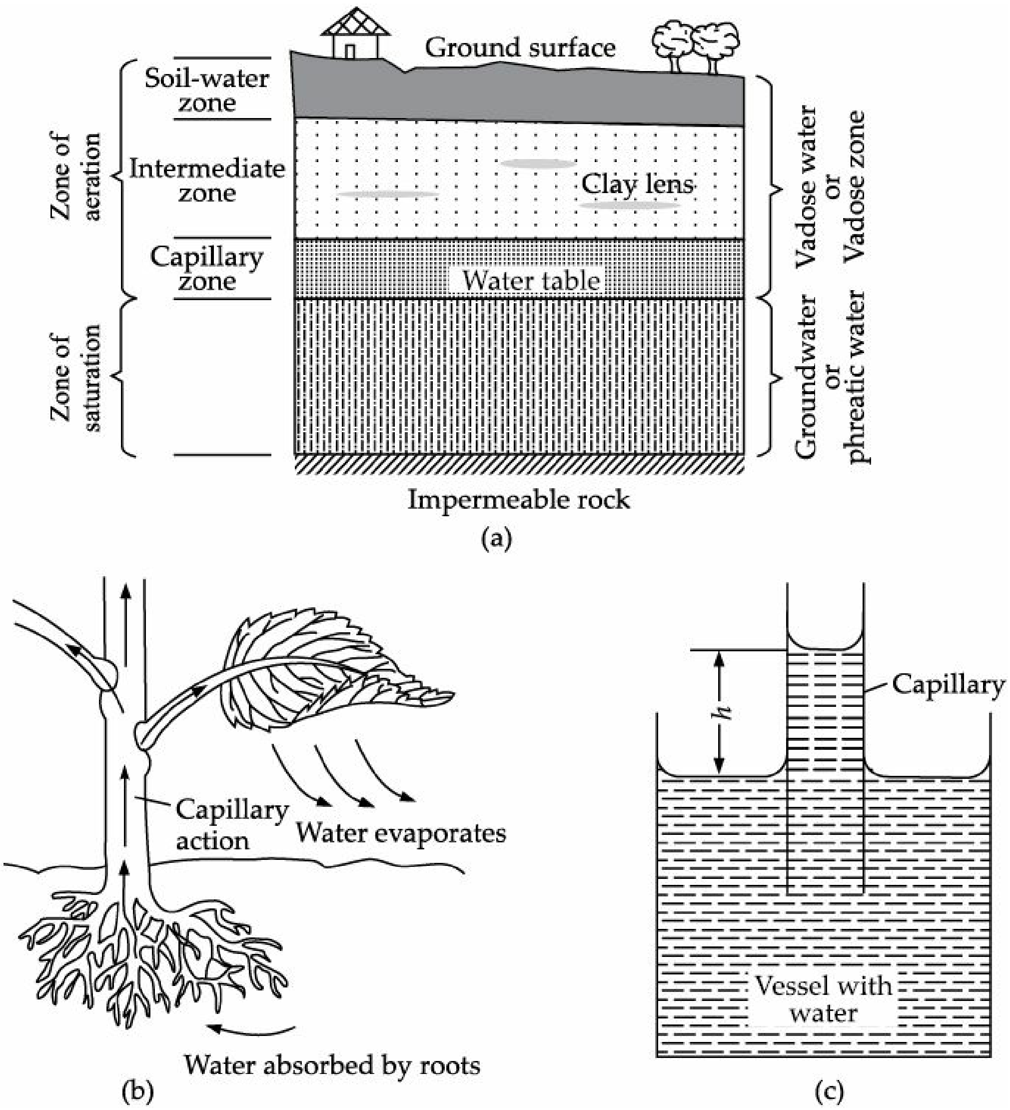


FIGURE 14.1 (a) Vertical distribution of groundwater, (b) rise of water in the plant, and (b) rise of water in capillary tube.

Data of the given problem

Effective grain size = 0.05 mm or 0.005 cm
Void ratio = 0.75

Solution

(a) Capillary rise (h_c): It is the ratio of the coefficient C to the effective grain size [Eq. (14.1)].

$$h_c = \frac{C}{eD_{10}} \tag{14.1}$$

where,

C = coefficient that varies from 0.1 to 0.5 cm^2, depending on the shape of grains and surface impurities

e = void ratio

D_{10} = effective grain size (mm) having 10% of finer

Therefore, $$h_c = \frac{0.1 \text{ to } 0.5}{0.75 \times 0.005} = 26.67 \text{ cm to } 133.33 \text{ cm}$$

(b) Type of soil: The value of capillary rise varies from 27 cm to 133 cm. Thus, the soil belongs to medium sand to silt type (Table 14.1). It indicates that the capillary rise increases with the decrease in grain size.

TABLE 14.1 Relation between Grain Size and Capillary Rise in Sedimentary Rocks

Material	*Grain size* (mm)	*Capillary rise* (cm)
Gravel	> 2	< 5
Coarse sand	2.0 – 0.6	5–15
Medium sand	0.6 – 0.2	15–40
Fine sand	0.2 – 0.06	40–70
Silt	0.06 – 0.002	100–150
Clay	< 0.002	> 150

PROBLEM 15 In an area of 1 km^2, the drop in water level is 6 m. If the porosity of the aquifer is 50% and the specific retention is 25%, estimate the (a) specific yield of the aquifer and (b) change of groundwater storage.

Key Concept Change in the groundwater storage depends on the area, annual water level fluctuation and specific yield of the aquifer material. The porosity of a soil or a rock layer is an important consideration when attempting to evaluate the potential volume of water it may contain, which is equal to specific yield and specific retention (Eq. 15.1).

$$\text{Porosity } (n) = S_y + S_r \tag{15.1}$$

where,

S_y = specific yield

S_r = specific retention

Data of the given problem

Area = 1 km^2 or 1 × 10^6 m

Drop in water level = 6 m

Porosity of the aquifer = 50% or 0.5

Specific retention = 25% or 0.25

Solution

(a) Specific yield of the aquifer (S_y): It is the volume of water released from groundwater storage per unit surface area of aquifer per unit decline in water table, which is the difference between porosity (n) and specific retention (S_r) [Eq. (15.2)].

$$S_y = n - S_r \tag{15.2}$$

Therefore, $$S_y = 0.50 - 0.25 = 0.25$$

(b) Change of groundwater storage: It is the product of area, water level fluctuation and specific yield, i.e.,

Area × Drop in water level × Specific yield

Therefore, groundwater storage = $1 \times 10^6 \times 6 \times 0.25 = 15{,}00{,}000$ m^3

PROBLEM 16 An unconfined aquifer extends over an area of 1 km^2. The initial water level in the aquifer is 33 m below ground level (bgl). The rise of water level is 32 m bgl after irrigation, with 18 cm depth of water. The drop of water level is 35.5 m bgl after pumping of water of 5×10^5 m^3. Estimate the (a) specific yield of the aquifer and (b) soil moisture deficiency before irrigation.

Key Concept Fluctuations in water level are caused by mainly two factors—(a) the rising of water level due to recharge of groundwater and (b) the falling of water level because of the withdrawal of water from aquifer body (Figure 16.1). Thus, the amount of water released from an aquifer is called *specific yield*.

Soil moisture deficit is an amount of water needed to bring the soil moisture content back to field capacity. Field capacity is the amount of water (soil moisture) the soil can hold against gravity, i.e., the maximum water a pot plant and not leak water.

Data of the given problem

Area = 1 km^2 or 1 × 10^6 m

Initial depth to water level = 33 m bgl

Rise of water level after irrigation = 32 m bgl

Depth of water column = 18 cm or 180 mm

Drop of water level after pumping = 35.5 m bgl

Pumped water = 5 × 10^5 m^3

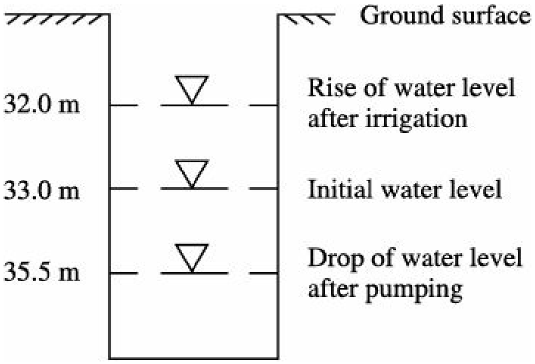


FIGURE 16.1 Water level changes.

Solution

(a) Specific yield (S_y): It is the ratio of the pumped water to the product of area and drop of water level [Eq. (16.1)], which is expressed in percentage (%).

$$S_y = \frac{\text{Pumped water}}{\text{Area} \times \text{Difference in drop of water level}} \tag{16.1}$$

Therefore,
$$S_y = \frac{5 \times 10^5}{1 \times 10^6 \times (35.5 - 32)} = 0.143 \text{ m or } 14.30\%$$

(b) Soil moisture deficiency before irrigation: It is the difference between depth of water column and recharge volume [Eq. (16.2)], which is expressed in millimetres (mm).

$$\text{Soil moisture deficiency before irrigation} = \text{Depth of water column} - \text{Recharge volume} \tag{16.2}$$

where, recharge volume is the product of area and specific yield [Eq. (16.3)], which is expressed
in millimetres (mm).

$$\text{Recharge volume} = \text{Area} \times \text{Specific yield} \tag{16.3}$$

If the aquifer area is 1 m^2, then the recharge volume $= 1 \times 1 \times 0.143$

$= 0.143$ m or 143 mm

Therefore, soil moisture deficiency before irrigation $= 180 - 143 = 37$ mm

PROBLEM 17 If the effective grain size of the aquifer material is 0.38 mm, determine the hydraulic conductivity, using Allen Hazen's formula.

Key Concept The hydraulic conductivity of a soil is a measure of the soil's ability to transmit water, when submitted to a hydraulic gradient. The grain size data can be used to estimate the hydraulic conductivity of sands, where the effective grain size is in between approximately 0.1 mm to 3.0 mm by applying the Allen Hazen's method. The effective grain size, D_{10}, is the size, which corresponds to 10% of the material being finer and 90% coarser. Thus, the aquifer material indicates a good porosity and the higher infiltration so that it has an ability to transmit water from one place to another.

Data of the given problem

Effective grain size of the aquifer material = 0.38 mm

Allen Hazen's formula (1905): It is an empirical formula for approximating hydraulic conductivity from grain size analyses [Eq. (17.1)], which is expressed in metre per day (m/day).

$$K = CD_{10}^2 \tag{17.1}$$

where,

K = hydraulic conductivity

C = constant or shape factor (850, Table 17.1)

D_{10} = effective grain size, 10% finer and 90% coarser (mm)

Therefore, $K = 850 \times 0.38^2 = 122.74$ m/day

TABLE 17.1 Shape Factor (C) or Constants of Coefficients of Various Grains

Grain	*Coefficient C*
Very closely packed sand	350
Very uniform clean sand	1,250
General range	700 to 1,000

Average	850

Shape factor is a dimensionless constant, depending on the various properties of the medium affecting flow other than the grain diameter (d) on which the dimensions of the pores depend.

PROBLEM 18 If the thickness of a semi-permeable layer is 3 m and its hydraulic conductivity is 10^{-3} m/day, estimate the hydraulic resistance.

Key Concept Besides hydraulic conductivity, there are some formation constants like transmissivity, storage coefficient, hydraulic diffusivity, hydraulic resistance, leakage factor and drainage factor, which are related to the properties of the aquifers and confining layers that govern the flow of water through them.

Data of the given problem

Thickness of the semi-permeable layer = 3 m

Hydraulic conductivity = 10^{-3} m/day or 0.001 m/day

Solution

Hydraulic resistance (C_r): It is the ratio of thickness of semi-permeable aquifer to its hydraulic conductivity [Eq. (18.1)], which is a useful index in semi-confined aquifers. This is expressed in days. If it is infinite, the aquifer is confined.

$$C_r = \frac{b'}{k'} \tag{18.1}$$

where,

b' = thickness of semi-permeable layer (m)
k' = hydraulic conductivity of semi-permeable layer (m/day)

Therefore, $$C_r = \frac{3}{10^{-3}} = 1{,}000 \text{ days}$$

PROBLEM 19 If the transmissivity of a semi-confined aquifer is 1,000 m^2/day and the hydraulic resistance is 250 days, determine the leakage factor of the aquifer.

Key Concept Leakage factor is an index of leakage, which represents the vertical percolation through a semi-permeable layer from above or below it. This is one of the formation constants like hydraulic conductivity, transmissivity, storage coefficient, hydraulic diffusivity, hydraulic resistance and drainage factor, which are related to the aquifer properties that govern the flow of water through them.

Data of the given problem

Transmissivity of the semi-confined aquifer = 1,000 m^2/day

Hydraulic resistance = 250 days

Solution

Leakage factor (L_f): It is the square root of the product of transmissivity [hydraulic conductivity (K) and aquifer thickness (b)] and hydraulic resistance [Eq. (19.1)]. This is expressed in metre (m). The greater the leakage factor, the smaller is the leakage.

$$L_f = \sqrt{KbC_r} \quad \text{or} \quad \sqrt{TC_r} \tag{19.1}$$

where,

T = transmissivity of the semi-confined aquifer (m^2/day)

C_r = hydraulic resistance of the semi-confined aquifer (days)

Therefore, $$L_f = \sqrt{1{,}000 \times 250} = 500 \text{ m}$$

PROBLEM 20 Hydraulic connectivity, specific yield and thickness of the unconfined fine sand aquifer material are 25 m^3/day, 6% and 25 m, respectively. If the distance between the pumping well and the observation well is 20 m, determine the (a) drainage factor and

(b) minimum pumping time (that yield is no longer delayed and Theis equation is applicable).

Key Concept *Drainage factor* is an index of drainability of the unconfined aquifer, which is one of the formation constants like hydraulic conductivity, transmissivity, storage coefficient, hydraulic diffusivity, hydraulic resistance and leakage factor, which are related to the properties of the aquifer materials that govern the flow of water through them. .

Data of the given problem

Hydraulic conductivity = 25 m^3/day

Specific yield = 6% or 0.06 × 60 × 24 (expressed in days)

Thickness of aquifer = 25 m

Distance between the pumping well and observation well = 20 m

Solution

(a) Drainage factor (B): It is the ratio of transmissivity (hydraulic conductivity and aquifer thickness) to specific yield of an aquifer [Eq. (20.1)] and is expressed in metres (m).

$$B = \sqrt{\frac{Kb}{\alpha S_y}} \quad \text{or} \quad \sqrt{\frac{T}{\alpha S_y}} \tag{20.1}$$

where,

K = hydraulic conductivity (m^3/day)

b = thickness of aquifer (m)

α = an empirical constant of the aquifer material (200 min for fine sand, Table 20.1) and its reciprocal $1/\alpha$ is called the *Boulton delay index*, which is expressed in days

S_y = specific yield of the aquifer

T = transmissivity of the unconfined aquifer material (m^2/day)

Therefore,
$$B = \sqrt{\frac{25 \times 5 \times 200}{0.06 \times 60 \times 24}} = 17.01 \text{ m}$$

(b) Pumping time (t_{wt}): It is the required time for pumping, which is defined as the ratio of distance between the pumping well and the observation well to the drainage factor [Eq. (20.2)].

$$t_{wt} = \frac{r}{B} \tag{20.2}$$

where,

r = distance between the pumping well and the observation well (m)
B = drainage factor (m)

Therefore,

$$t_{wt} = \frac{20}{17.01} = 1.18$$

The value of αt_{wt} for 1.18 of t_{wt} (Figure 20.1) = 4.9

Therefore,

$$t_{wt} = \frac{\alpha t_{wt}}{\alpha} \tag{20.3}$$

$$t_{wt} = 4.9 \times \frac{200}{60 \times 24} = 0.68 \text{ day}$$

TABLE 20.1 Boulton Delay Index (Prickett, 1965)

Material	*Boulton delay index*
Coarse sand	10 min
Medium sand	60 min
Fine sand	200 min
Very fine sand	1,000 min
Silt	2,000 min

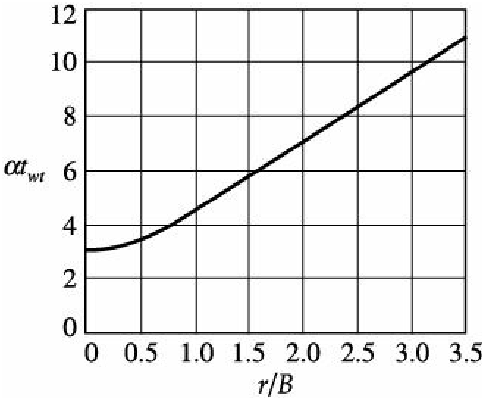


FIGURE 20.1 Boulton's delay (1963) index curve.

PROBLEM 21 The storage coefficient of confined aquifer of 40 m thickness is 4×10^{-4}. If the porosity of the aquifer is 0.25, estimate the fraction of storativity coefficient attributable to compressibility of the aquifer skeleton and expansibility of water.

Key Concept *Storativity* is an ability of an aquifer to store water. A change in volume of stored water due to change in piezometric head and a change of water release (taken up) from aquifer per unit decline (rise) in piezometric head is termed as *storativity* (Figure 21.1). This is caused by a combined action of compressibility of the aquifer skeleton and expansibility of the water, as the aquifer material acts as an elastic material.

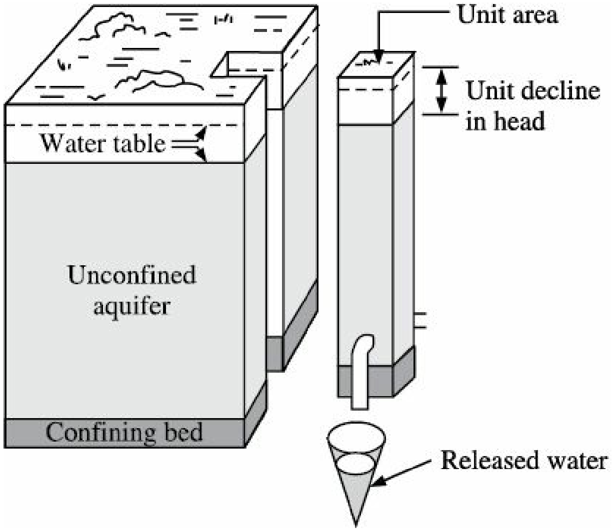


FIGURE 21.1 Aquifer storage.

Data of the given problem

Storativity coefficient of the aquifer = 4×10^{-4}

Thickness of the aquifer = 40 m

Porosity of the aquifer = 0.25

Solution

Storativity (S): It is the sum of expansibility of the water and compressibility of the aquifer skeleton [Eq. (21.1)], which is a dimensionless unit.

$$S = \gamma n b \beta + \gamma \alpha b \tag{21.1}$$

Then,

$$\gamma \alpha b = S - \gamma n b \beta \tag{21.2}$$

where,

S = coefficient of storativity (dimensionless)

$\gamma n b \beta$ = expansibility of water

$\gamma \alpha b$ = compressibility of aquifer skeleton

γ = specific weight of water (0.1 $\text{kg/cm}^2\text{/m}$)

β = compressibility of the reciprocal of the bulk modulus of elasticity of water (4.7×10^{-5} $\text{cm}^2\text{/kg}$), and

α = bulk modulus of compressibility of the aquifer material (1,000 kg/cm^3)

Fraction of compressibility of the aquifer skeleton,

$$\gamma\alpha b = 4 \times 10^{-4} - 0.1 \times 0.25 \times 4.7 \times 10^{-5} \times 40$$

$$\gamma\alpha b = 3.53 \times 10^{-4}$$

The compressibility of the aquifer skeleton ($\gamma\alpha b$) is 3.53×10^{-4} for the aquifer storativity (S) of 4×10^{-4}.

If the storativity is 100, then the fraction of compressibility of the aquifer skeleton is

$$\gamma\alpha b = \frac{\gamma\alpha b}{S} \times 100 \tag{21.3}$$

Therefore, $$\gamma\alpha b = \frac{3.53 \times 10^{-4}}{4 \times 10^{-4}} \times 100 = 88.25\%$$

$$\text{Fraction of expansibility of water } (\gamma nb\beta) = 100 - \gamma\alpha b \tag{21.4}$$

Therefore, $$\gamma nb\beta = 100 - 88.25 = 11.75\%$$

PROBLEM 22 In a confined aquifer, the barometric efficiency of a well is 65%. If the thickness of the aquifer is 50 m and the porosity is 25%, estimate the coefficient of storage of the aquifer.

Key Concept Changes in the atmosphere pressure (barometric tides) produce sizable fluctuations in wells of confined aquifers. An increase in the atmospheric pressure causes a decrease in the water levels and vice versa, which is called *barometric efficiency* (*BE*). This is related to water properties, including the storage coefficient.

Data of the given problem

Barometric efficiency = 65% or 0.65

Thickness of the aquifer = 50 m

Porosity of the aquifer = 25% or 0.25

Solution

Coefficient of storage of the aquifer (S): It is the product of specific weight of the water, porosity and thickness of the aquifer, and their activities [Eq. (22.1)], which is expressed in a dimensionless unit.

$$S = \gamma n b \beta \left(1 + \frac{\alpha}{n\beta}\right) \tag{22.1}$$

where,

γ = specific weight of the water (0.1 kg/cm^2/m)

n = porosity of the aquifer

b = thickness of the aquifer

β = bulk modulus of compression of the water (reciprocal of the bulk modulus of elasticity) (4.7×10^{-5} cm^2/kg)

α = bulk modulus of compression of the aquifer skeleton (1,000 kg/cm^3)

$1 + \frac{\alpha}{n\beta}$ = reciprocal of the barometric efficiency $\left(\frac{1}{BE}\right)$

Therefore, $$S = 0.1 \times 0.25 \times 4.7 \times 10^{-5} \times 50 \times \frac{100}{65}$$

$$S = 9.05 \times 10^{-5}$$

PROBLEM 23 The tidal efficiency of a well in a confined aquifer overlain by an extensive body of tide water is 42%. If the thickness of the aquifer is 40 m and the porosity is 0.30, estimate the bulk modulus of the compression of the aquifer skeleton.

Key Concept In coastal aquifers which are in contact with the ocean, sinusoidal fluctuations of groundwater levels occur in response to tides. Contrary to the atmospheric pressure effect, the tidal fluctuations are direct, i.e., as the sea level increases, the groundwater level also increases. This relation is called *tidal efficiency* (*TE*), which is defined as the ratio of the water level amplitude to the tidal amplitude. Thus, the TE is a measure of the incompetence of overlying confined beds to resist pressure changes.

Data of the given problem

Tidal efficiency = 42% or 0.42

Thickness of the aquifer = 40 m

Porosity of the aquifer = 0.30

Solution

Bulk modulus of compression of the aquifer skeleton (α): It is a measure of rock’s susceptibility to volume changes in response to external force acting on it [Eqs. (23.1 to 23.4)] which is expressed in kilogram per cubic metres (kg/cm^3).

$$\text{Storage coefficient } (S) = \gamma n b \beta \left(\frac{1}{BE} \right) \tag{23.1}$$

Also,
$$S = \gamma n b \beta + \gamma \alpha b \tag{23.2}$$

Then,
$$\gamma \alpha b = S - \gamma n b \beta \tag{23.3}$$

Then,
$$\alpha = \frac{S - \gamma n b \beta}{\gamma b} \tag{23.4}$$

where,

S = coefficient of storage (dimensionless)
γ = specific weight of water (0.1 kg/cm^2/m)
n = porosity of aquifer
b = thickness of aquifer (m)
β = compressibility of the reciprocal of the bulk modulus of elasticity of water (4.7 × 10^{-5} cm^2/kg)
α = bulk modulus of compression of the aquifer skeleton (1,000 kg/cm^3)
BE = barometric efficiency
$\gamma n b \beta$ = expansion of the water
$\gamma \alpha b$ = compression of the aquifer skeleton

$$BE + TE = 1 \tag{23.5}$$

where,

TE = tidal efficiency

or $BE = 1 - TE$ (23.6)

$$BE = 1 - 0.42 = 0.58$$

$$S = 0.1 \times 0.30 \times 40 \times 4.7 \times 10^{-5} \times \frac{1}{0.58}$$

$$= 9.72 \times 10^{-5}$$

Therefore,
$$\alpha = \frac{9.72 \times 10^{-5} - (0.1 \times 0.30 \times 40 \times 4.7 \times 10^{-5})}{0.1 \times 40}$$

$$= 1.02 \times 10^{-5}$$

PROBLEM 24 In an area, the water pressure in a confined aquifer is reduced by 12 kg/cm^2. Thickness of the aquifer is 35 m. The porosity and storage coefficient of the aquifer are 25% and 1.90 × 10^{-4}, respectively. Estimate the probable land subsidence caused by lowering of water pressure.

Key Concept The increasing exploitation of groundwater, especially in basins filled with unconsolidated alluvial, lacustrine, or shallow marine deposits, has, as one of its consequences, the sinking or settlement of the land surface, which is called *land subsidence*. The occurrence of major land subsidence due to the withdrawal of groundwater is relatively common in highly developed areas. This depends on the change in water pressure in the aquifer body.

Data of the given problem

Reduction in the water pressure = 12 kg/cm^2

Thickness of the aquifer = 35 m

Porosity of the aquifer = 25% or 0.25

Storage coefficient = 1.90×10^{-4}

Solution

Amount of land subsidence (Δb): It is the product of the change in water pressure with relation to aquifer response [Eq. (24.1)], which is expressed in metre (m).

$$\Delta b = \Delta p\left(\frac{S}{\gamma} - nb\beta\right) \tag{24.1}$$

where,

Δb = amount of land subsidence (m)
Δp = change (decline) in water pressure (kg/cm^2)
S = storage coefficient (dimensionless)
γ = specific weight of water per unit area (0.1 kg cm^{-2}m^{-1})
n = porosity of aquifer
b = thickness of aquifer (m)
β = bulk modulus of compression of the water (4.74×10^{-5} cm^{2}kg^{-1})

Therefore,

$$\Delta b = 12\left(\frac{1.90 \times 10^{-4}}{0.1} - 0.25 \times 35 \times 4.74 \times 10^{-5}\right) = 0.018 \text{ m}$$

PROBLEM 25 Three wells, *A*, *B* and *C*, are located in a triangle direction with a space of 3,000 m among them. The contour elevations at the respective wells are 65, 40 and 20 m amsl. The water levels in the wells are 35, 20 and 5 m bgl. The effective porosity of the aquifer material is 0.12 and the hydraulic conductivity is 20 m/day. Determine the (a) direction of the groundwater flow, (b) hydraulic gradient and (c) velocity of the groundwater flow.

Key Concept Groundwater moves from the areas of higher elevation or higher pressure/hydraulic head (recharge areas) to the areas of lower elevation or pressure/hydraulic head. This is where the groundwater is released into streams, lakes, wetlands or springs (discharge areas). The base flow of streams and rivers, which is the sustained flow between the storm events, is provided by groundwater. The direction of groundwater flow normally follows the general topography of the land surface, depending upon the porosity and permeability of the ground material, and gravity of the water, which gives information on the hydraulic gradient and velocity of the groundwater flow.

Data of the given problem

Space between the wells = 3,000 m

Contour elevations at wells *A*, *B* and *C* = 65, 40 and 20 m amsl

Water levels in wells *A*, *B* and *C* = 35, 20 and 5 m bgl

Difference in water levels between two wells = 15 m (35 – 20 m or 20 – 5 m)

Effective porosity of the aquifer material = 0.12

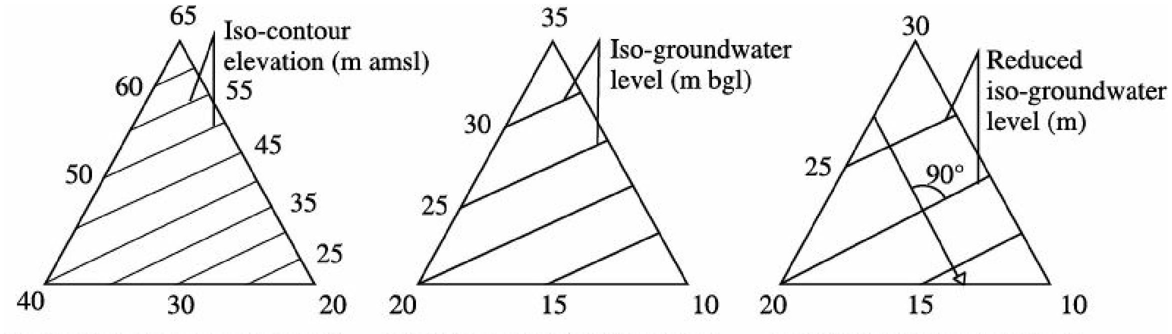
Hydraulic conductivity of the aquifer material = 20 m/day

Solution

(a) Direction of the groundwater flow

Reduced water level (m): It is the difference between contour elevation and water level, i.e.,

Contour elevation (m amsl) – Water level (m bgl)



(a) Contour elevation (m amsl) (b) Groundwater level (m bgl) (c) Reduced water level (m)

FIGURE 25.1 Direction of the groundwater flow.

As observed from Figure 25.1, the direction of the groundwater flow is NW-SE.

(b) Hydraulic gradient (*i*): It is a slope of the water table or potentiometric surface, which is caused by a change in hydraulic head over the change in distance between the two monitoring wells [Eq. (25.1)].

$$i = \frac{dh}{dl} \quad \text{or} \quad \frac{h_2 - h_1}{l} \tag{25.1}$$

where,

dh or $h_2 - h_1$ = difference of water levels between upstream and downstream points or between wells

dl or l = distance between contours or wells (m)

Therefore,
$$i = \frac{15}{3{,}000} = 0.005$$

(c) Velocity of the groundwater flow (*v*): It is the flow per unit cross-sectional area of the porous medium, which is a quantity of hydraulic conductivity and hydraulic gradient through porous material [Eq. (25.2)]. This is expressed in metre per day (m/day).

$$v = \frac{ki}{n} \tag{25.2}$$

where,

k = hydraulic conductivity (m/day)

i = hydraulic gradient

n = effective porosity

Therefore,
$$v = \frac{20 \times 0.005}{0.12} = 0.83 \text{ m/day}$$

4

Groundwater Flow

PROBLEM 26 The flow of groundwater is in longitudinal direction in an alluvial valley of unconfined aquifer (Figure 26.1). Hydraulic conductivity of the aquifer material is 30 m/day. Two piezometers are located at a distance of 500 m apart from the central line of the valley. The water level in the piezometer I (located at upstream side) is 1.0 m and is 1.5 m in the piezometer II (located at downstream side) from the ground surface. The average height of the aquifer material between these two piezometers is 60 m and the average width of the aquifer material is 3,000 m. Work out the following with neat sketch:

a. What is the velocity of the groundwater flow?
b. If the porosity of the aquifer material is 30%, compute the travelling time of water from the head of the valley to the point of 15 km downstream.
c. If the consumption of water per head day is 140 litre (l), estimate the population which acquires groundwater.

Key Concept The movement, travelling distance and travelling time of the groundwater from one area (upstream) to another area (downstream) depend on the porosity and permeability of the aquifer material (including thickness and width) with respect to the topography. This gives clue on the velocity of groundwater flow, travelling time of water and availability of the groundwater resources. According to the usage of the available groundwater, it can be possible to estimate the population which acquires groundwater.

Data of the given problem

Hydraulic conductivity of the aquifer material = 30 m/day

Distance between the two piezometers = 500 m

Difference of water levels between the two piezometers = 0.5 m (1.5 – 1.0 m)

Average height of the aquifer material = 60 m

Width of the aquifer material = 3,000 m

Porosity of the aquifer material = 30% or 0.30

Travelling distance of water or length = 15 km or 15,000 m

Consumption of water per head per day = 140 l

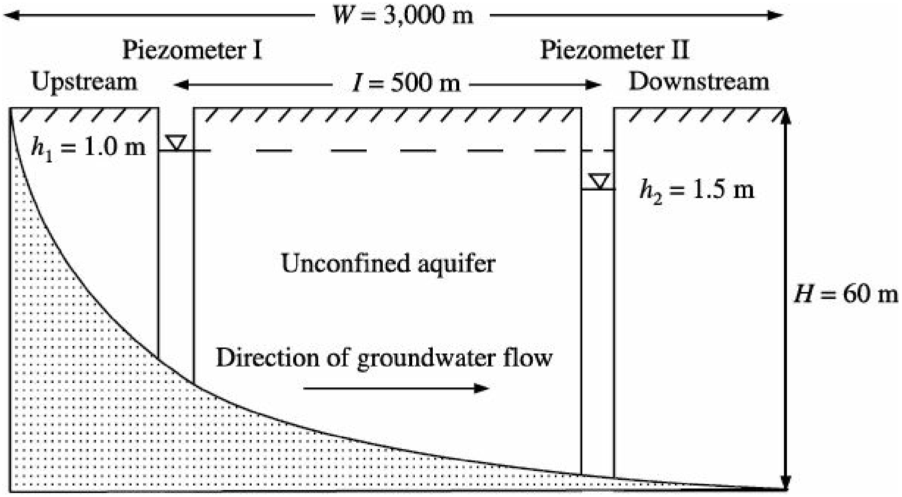


FIGURE 26.1 Groundwater flow in a longitudinal direction in an alluvial valley of unconfined aquifer

(**a) Velocity of groundwater flow (*v*):** It is the rate of flow of water that is equal to hydraulic conductivity and hydraulic gradient [which is the difference of water levels with respect to distance of the two wells; [Eq. (26.1)]. This is expressed in metre per day (m/day).

$$v = Ki \tag{26.1}$$

where,

K = hydraulic conductivity (m/day)

i = hydraulic gradient $\left(\frac{h_2 - h_1}{l}\right)$

h_1 = water level at piezometer – I (m)

h_2 = water level at piezometer – II (m)

l = distance between two piezometers

Therefore, $$v = 30 \times \frac{1.5 - 1.0}{500} = 0.03 \text{ m/day}$$

(**b) Travelling time of water (T_w):** It is the ratio of travelling distance to the velocity of the groundwater flow [Eq. (26.2)], which is expressed in year.

$$T_w = \frac{L}{v} \times n \tag{26.2}$$

where,

L = travelling distance of water or length (km)

v = velocity of the groundwater flow (m/day)

n = porosity of aquifer material

Therefore, $$T_w = \frac{15{,}000}{0.03} \times \frac{30}{100} \times \frac{1}{365}$$

$$T_w = 410.96 \quad \text{or} \quad 411 \text{ years}$$

(c) Population acquiring the groundwater (P_g): It is the ratio of the total quantity of water flowing to the consumption of water [Eq. (26.3)].

$$P_g = \frac{Q}{C_w} \tag{26.3}$$

Also, $$Q = v \times A$$

and $$A = W \times H$$

where,

Q = total quantity of water flowing into the aquifer

C_w = consumption of water per head per day (l)

v = velocity of the groundwater flow (m/day)

A = area of cross-section of the valley

W = width of aquifer material (m)

H = height of aquifer material (m)

Then, $A = 3{,}000 \times 60 = 1{,}80{,}000$ m

and $Q = 0.03 \times 1{,}80{,}000$

$= 5{,}400\ \text{m}^3/\text{day}$ or $54{,}00{,}000$ l/day

Therefore, $$P_g = \frac{54{,}00{,}000}{140} = 38{,}571.43 \quad \text{or} \quad 38{,}570 \text{ (say)}$$

Thus, the availability of groundwater is 5,400 m^3/day, which can be utilised by 38,570 people.

PROBLEM 27 The required time for tracer to travel from which are well to another which are 15 m apart is 3 hours (Figure 27.1). The difference of water table elevations between these two wells is 0.5 m. The average grain size of the aquifer material is 1 mm. The dynamic viscosity of the water is 0.008×10^{-4} stoke at 27°C. The porosity of the aquifer is 20%. Determine the (a) hydraulic conductivity, (b) seepage velocity and (c) Reynold's number.

Key Concept Hydrological tracers (dyes, salts, and stable isotopes) can be used to characterise a watershed. They are added to a water body to help to constrain the residence time or the time it takes for a molecule of water to flow from one well-point to another well-point to characterise the inputs and outflows of water (i.e., from where the water comes and where it goes), and to determine mixing and flow paths of water within a system (how it gets from one point to another). This provides information on the nature of hydraulic conductivity, seepage velocity and Reynold's number of the water flow (which is used to distinguish the flow of groundwater whether it is turbulent or laminar).

Data of the given problem

Travel distance of tracer between the two wells = 15 m

Required time for tracer to travel between the two wells = 3 hours

Porosity of the aquifer = 20% or 0.20

Water-table elevation between the two wells = 0.5 m

Grain size of the aquifer material = 1 mm or 0.001 m or 1×10^{-3}

Dynamic viscosity of the water = 0.008 stoke at 27°C

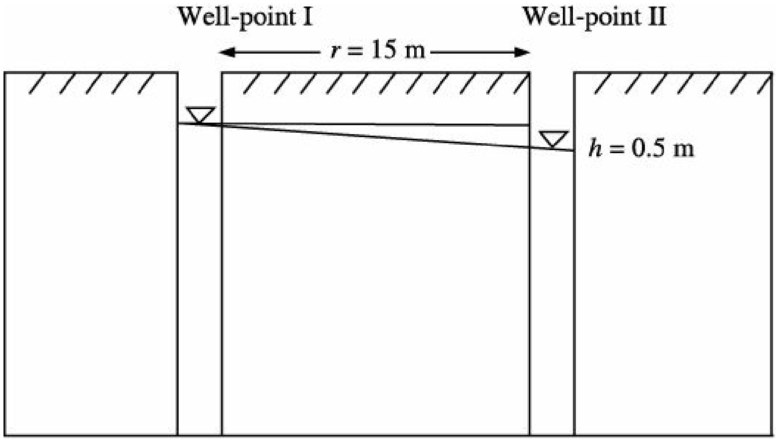


FIGURE 27.1 Travel of tracer along groundwater flow.

Solution

(a) Hydraulic conductivity (*K*): It is a measure of material's capacity to transmit water from one place to another.

Actual velocity of tracer through the aquifer (V_a): It is the travel distance of tracer with respect to time between the two wells [Eq. (27.1)], which is expressed in metre per day (m/day) or metre per hour (m/hour).

$$V_a = \frac{r}{t} \tag{27.1}$$

where,

r = travel distance of tracer between two wells (m)
t = required time for tracer to travel between two wells (min or hour)

Therefore, $$V_a = \frac{15}{3} = 3 \text{ m/hour}$$

(b) *Seepage velocity* (*V*): It is the rate of discharge of seepage water through a porous medium per unit area of void space perpendicular to the direction of the flow, which is defined as the product of hydraulic conductivity and hydraulic gradient [Eq. (27.2)]. This is expressed in m/day.

As per Darcy's law, $$V = Ki = K\frac{h}{L} \tag{27.2}$$

where,

K = hydraulic conductivity (m/day)
h = Water table elevation between the two wells (m)
i = hydraulic gradient
L = length between the two wells (m)

Therefore, $$V = K\frac{0.5}{15} = \frac{K}{30}$$

Actual velocity of tracer move through a permeable material (V_a)*:* It is the rate of seepage velocity with respect to aquifer porosity [Eq. (27.3)], which is expressed in m/day.

$$V_a = \frac{V}{n} \tag{27.3}$$

where,

V = seepage velocity (m/day)
n = porosity of the aquifer

Since the actual velocity of tracer through the aquifer (V_a) is 3 m/hour,

$$K = V_a \times V \times n \tag{27.4}$$

$$K = 3 \times 30 \times 0.20 = 18 \text{ m/hour} \quad \text{or} \quad 432 \text{ m/day}$$

Then, seepage velocity (V) = $$\frac{K}{30} \tag{27.5}$$

Therefore, $$V = \frac{432}{30} = 14.4 \text{ m/day or } 0.017 \text{ cm/s or } 1.7 \times 10^{-4}$$

(c) Reynold's number (R_e): It is the number used for determination of fluid flow whether it is laminar or turbulent, which is defined as the ratio of the seepage velocity of grain size to the dynamic viscosity of water [Eq. (27.6)].

$$R_e = \frac{Vd_m}{\mu} \tag{27.6}$$

where,

V = seepage velocity (cm/s)
d_m = grain size of the aquifer material (mm)
μ = dynamic viscosity of the water

Therefore, $$R_e = \frac{0.017}{100} \times \frac{1}{1,000} \times \frac{1}{0.008 \times 10^{-4}}$$

$$R_e = 0.2125 \quad \text{or} \quad 0.21$$

PROBLEM 28 The transmissivity and storativity of a non-leaky confined aquifer in an area are 1,500 m^2/day and 0.0003, respectively. A full penetrating production well yields water at a constant rate of 2,000 m^3/day for a period of one year. If the distance between the production well and observation well is 150 m (Figure 28.1), estimate the drawdown for a pumping period of 100, 200 and 300 days, respectively.

Key Concept A difference of water level between the initial water level (static water level) and the pumping water level (dynamic water level) is known as *drawdown*, which is caused by the pumping of well. A curve or cone developed between the pumping well and observation well is called *drawdown curve* or *cone of depression*. The drawdown increases with the increase in pumping time due to corresponding withdrawal of groundwater. Thus, the higher the pumping rate, the greater is the drawdown.

Data of the given problem

Transmissivity of the confined aquifer = 1,500 m^2/day

Storativity of the confined aquifer = 0.0003

Discharge of the production well = 2,000 m^3/day

Time for estimation of drawdown = 100, 200 and 300 days

Distance between the production well and observation well = 150 m

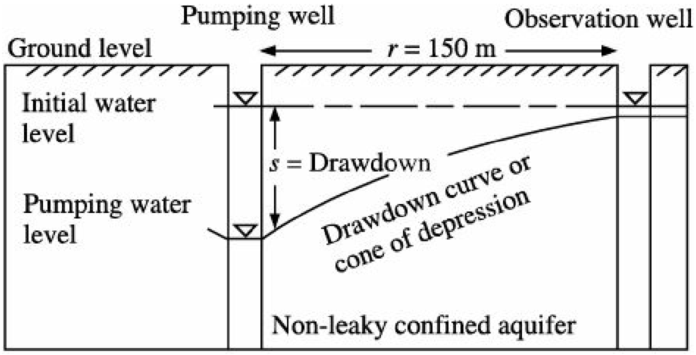


FIGURE 28.1 Drawdown curve.

Solution

Transmissivity (*T*): It is the rate of flow under a unit hydraulic gradient through a unit width of aquifer of thickness, which is defined as the ratio of well discharge to drawdown [Eq. (28.1)]. This is expressed in square metre per day (m^2/day).

$$T = \frac{Q}{4\pi s} W(u) \tag{28.1}$$

or

$$s = \frac{Q}{4\pi T} W(u) \tag{28.2}$$

where,

T = transmissivity (m^2/day)

Q = discharge of the well (m^3/day)

s = drawdown [It is the difference of static water level and pumping water level, which
is defined as the ratio of well discharge to transmissivity, as shown in [Eq. (28.2)]. This is expressed in metre (m).]

$W(u)$ = well function of u

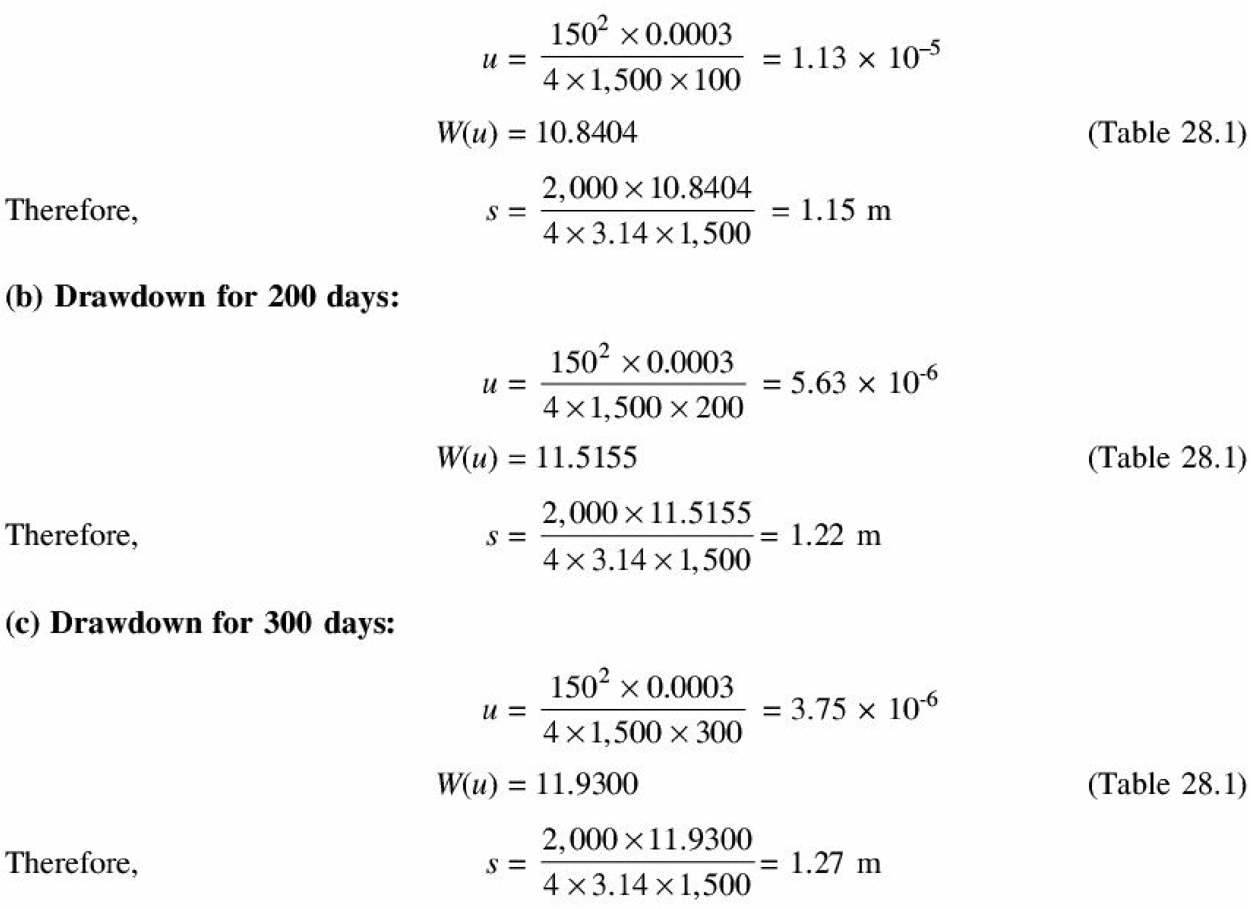
u = argument of the well $\left(\frac{r^2 S}{4Tt}\right)$

Here, r = radial distance from production well to observation well

S = storage coefficient (dimensionless)

t = time since pumping started (days)

(a) Drawdown for 100 days:



$$u = \frac{150^2 \times 0.0003}{4 \times 1{,}500 \times 100} = 1.13 \times 10^{-5}$$

$$W(u) = 10.8404 \qquad \text{(Table 28.1)}$$

Therefore, $$s = \frac{2{,}000 \times 10.8404}{4 \times 3.14 \times 1{,}500} = 1.15 \text{ m}$$

(b) Drawdown for 200 days:

$$u = \frac{150^2 \times 0.0003}{4 \times 1{,}500 \times 200} = 5.63 \times 10^{-6}$$

$$W(u) = 11.5155 \qquad \text{(Table 28.1)}$$

Therefore, $$s = \frac{2{,}000 \times 11.5155}{4 \times 3.14 \times 1{,}500} = 1.22 \text{ m}$$

(c) Drawdown for 300 days:

$$u = \frac{150^2 \times 0.0003}{4 \times 1{,}500 \times 300} = 3.75 \times 10^{-6}$$

$$W(u) = 11.9300 \qquad \text{(Table 28.1)}$$

Therefore, $$s = \frac{2{,}000 \times 11.9300}{4 \times 3.14 \times 1{,}500} = 1.27 \text{ m}$$

TABLE 28.1 Values of Well Function *[W(u)]* for Values of *u* between 10^{-15} and 9.9 (Wenzel, 1942)

u→ **N ↓**	$N \times 10^{-15}$	$N \times 10^{-14}$	$N \times 10^{-13}$	$N \times 10^{-12}$	$N \times 10^{-11}$	$N \times 10^{-10}$	$N \times 10^{-9}$	$N \times 10^{-8}$	$N \times 10^{-7}$	$N \times 10^{-6}$	$N \times 10^{-5}$	$N \times 10^{-4}$	$N \times 10^{-}$
1.0	33.9616	31.6590	29.3564	27.0538	24.7512	22.4486	20.1460	17.8435	15.5409	13.2383	10.9357	8.6332	6.33
1.1	33.8662	31.5637	29.2611	26.9585	24.6559	22.3533	20.0507	17.7482	15.4456	13.1430	10.8404	8.5379	6.23
1.2	33.7792	31.4767	29.1741	26.8715	24.5689	22.2663	19.9637	17.6611	15.3586	13.0560	10.7534	8.4509	6.14
1.3	33.6692	31.3966	29.0940	26.7914	24.4889	22.1863	19.8837	17.5811	15.2785	12.9758	10.6734	8.3709	6.06
1.4	33.6251	31.3225	29.0199	26.7173	24.4147	22.1122	19.8096	17.5070	15.2044	12.9018	10.5993	8.2968	5.99
1.5	33.5561	31.2535	28.9509	26.6483	24.3458	22.0432	19.7406	17.4380	15.1354	12.8328	10.5303	8.2278	5.92
1.6	33.4916	31.1890	28.8864	26.5838	24.2812	21.9786	19.6760	17.3735	15.0709	12.7683	10.4657	8.1634	5.86
1.7	33.4309	31.1283	28.8258	26.5232	24.2206	21.9180	19.6154	17.3128	15.0103	12.7077	10.4051	8.1027	5.80
1.8	33.3738	31.0712	28.7686	26.4660	24.1634	21.8608	19.5583	17.2557	14.9531	12.6505	10.3479	8.0445	5.74
1.9	33.3197	31.0171	28.7145	26.4119	24.1094	21.8068	19.5042	17.2016	14.8990	12.5964	10.2939	7.9915	5.69
2.0	33.2684	30.9658	28.6632	26.3607	24.0581	21.7555	19.4529	17.1503	14.8477	12.5451	10.2426	7.9402	5.63
2.1	33.2196	30.9170	28.6145	26.3119	24.0093	21.7067	19.4041	17.1015	14.7989	12.4964	10.1938	7.8914	5.59

2.2	33.1731	30.8705	28.5679	26.2653	23.9628	21.6602	19.3576	17.0550	14.7524	12.4498	10.1473	7.8449	5.54
2.3	33.1286	30.8261	28.5235	26.2209	23.9183	21.6157	19.3131	17.0106	14.7080	12.4054	10.1028	7.8004	5.49
2.4	33.0861	30.7835	28.4809	26.1783	23.8758	21.5732	19.2706	16.9680	14.6654	12.3628	10.0603	7.7579	5.45
2.5	33.0453	30.7427	28.4401	26.1375	23.8349	21.5323	19.2298	16.9272	14.6246	12.3220	10.0194	7.7172	5.41
2.6	33.0060	30.7035	28.4009	26.0983	23.7957	21.4931	19.1905	16.8880	14.5854	12.2828	9.9802	7.6779	5.37
2.7	32.9683	30.6657	28.3631	26.0606	23.7580	21.4554	19.1528	16.8502	14.5476	12.2450	9.9425	7.6401	5.34
2.8	32.9319	30.6294	28.3268	26.0242	23.7216	21.4190	19.1164	16.8138	14.5113	12.2087	9.9061	7.6038	5.30
2.9	32.8968	30.5943	28.2917	25.9891	23.6865	21.3839	19.0813	16.7788	14.4762	12.1736	9.8710	7.5687	5.26
3.0	32.8629	30.5604	28.2578	25.9552	23.6526	21.3500	19.0474	16.7449	14.4423	12.1397	9.8371	7.5348	5.23
3.1	32.8302	30.5276	28.2250	25.9224	23.6198	21.3172	19.0146	16.7121	14.4095	12.1069	9.8043	7.5020	5.20
3.2	32.7984	30.4958	28.1932	25.8907	23.5880	21.2855	18.9829	16.6803	14.3777	12.0751	9.7726	7.4703	5.17
3.3	32.7676	30.4651	28.1625	25.8599	23.5573	21.2547	18.9521	16.6495	14.3470	12.0444	9.7418	7.4395	5.13
3.4	32.7378	30.4352	28.1326	25.8300	23.5274	21.2249	18.9223	16.6197	14.3171	12.0145	9.7120	7.4097	5.11
3.5	32.7088	30.4062	28.1036	25.8010	23.4985	21.1959	18.8933	16.5907	14.2881	11.9855	9.6830	7.3807	5.081
3.6	32.6806	30.3780	28.0755	25.7729	23.4703	21.1677	18.8651	16.5625	14.2599	11.9574	9.6548	7.3526	5.05
3.7	32.6532	30.3506	28.0481	25.7455	23.4429	21.1403	18.8377	16.5351	14.2325	11.9300	9.6274	7.3252	5.02
3.8	32.6266	30.3240	28.0214	25.7188	23.4162	21.1136	18.8110	16.5085	14.2059	11.9033	9.6007	7.2985	4.99
3.9	32.6006	30.2980	27.9954	25.6928	23.3902	21.0877	18.7851	16.4825	14.1799	11.8773	9.5748	7.2725	4.97
4.0	32.5753	30.2727	27.9701	25.6675	23.3649	21.0623	18.7598	16.4572	14.1546	11.8520	9.5495	7.2472	4.94
4.1	32.5506	30.2480	27.9454	25.6428	23.3402	21.0376	18.7351	16.4325	14.1299	11.8273	9.5248	7.2225	4.92
4.2	32.5265	30.2239	27.9213	25.6187	23.3161	21.0136	18.7110	16.4084	14.1058	11.8032	9.5007	7.1985	4.89
4.3	32.5029	30.2004	27.8978	25.5952	23.2926	20.9900	18.6874	16.3884	14.0823	11.7797	9.4771	7.1749	4.87
4.4	32.4800	30.1774	27.8748	25.5722	23.2696	20.9670	18.6644	16.3619	14.0593	11.7567	9.4541	7.1520	4.85
4.5	32.4575	30.1549	27.8523	25.5497	23.2471	20.9446	18.6420	16.3394	14.0368	11.7342	9.4317	7.1295	4.831
4.6	32.4355	30.1329	27.8303	25.5277	23.2252	20.9226	18.6200	16.3174	14.0148	11.7122	9.4097	7.1075	4.80
4.7	32.4140	30.1114	27.8088	25.5062	23.2037	20.9011	18.5985	16.2959	13.9923	11.6907	9.3882	7.0860	4.78
4.8	32.3929	30.0904	27.7878	25.4852	23.1826	20.8800	18.5774	16.2748	13.9723	11.6697	9.3671	7.0650	4.76
4.9	32.3723	30.0697	27.7672	25.4646	23.1620	20.8594	18.5568	16.2542	13.9516	11.6491	9.3465	7.0444	4.74
5.0	32.3521	30.0495	27.7470	25.4444	23.1418	20.8392	18.5366	16.2340	13.9314	11.6289	9.3263	7.0242	4.72
5.1	32.3323	30.0297	27.7271	25.4246	23.1220	20.8194	18.5168	16.2142	13.9116	11.6091	9.3065	7.0044	4.70
5.2	32.3129	30.0103	27.7077	25.4051	23.1026	20.8000	18.4974	16.1948	13.8922	11.5896	9.2871	6.9850	4.68
5.3	32.2939	29.9913	27.6887	25.3861	23.0835	20.7809	18.4783	16.1758	13.8732	11.5706	9.2681	6.9659	4.66
5.4	32.2752	29.9726	27.6700	25.3674	23.0648	20.7622	18.4596	16.1571	13.8545	11.5519	9.2494	6.9473	4.64

5.5	32.2568	29.9542	27.6516	25.3491	23.0465	20.7439	18.4413	16.1387	13.8361	11.5336	9.2310	6.9289	4.631
5.6	32.2388	29.9362	27.6336	25.3310	23.0285	20.7259	18.4233	16.1207	13.8181	11.5155	9.2130	6.9109	4.613
5.7	32.2211	29.9185	27.6159	25.3133	23.0108	20.7082	18.4056	16.1030	13.8004	11.4978	9.1953	6.8932	4.595
5.8	32.2037	29.9011	27.5985	25.2959	22.9934	20.6908	18.3882	16.0856	13.7830	11.4804	9.1779	6.8758	4.578
5.9	32.1866	29.8840	27.5814	25.2789	22.9763	20.6737	18.3711	16.0685	13.7659	11.4633	9.1608	6.8588	4.561
6.0	32.1698	29.8672	27.5646	25.2620	22.9595	20.6569	18.3543	16.0517	13.7491	11.4465	9.1440	6.8420	4.544
6.1	32.1533	29.8507	27.5481	25.2455	22.9429	20.6403	18.3378	16.0352	13.7326	11.4300	9.1275	6.8254	4.528
6.2	32.1370	29.8344	27.5318	25.2293	22.9267	20.6241	18.3215	16.0189	13.7163	11.4138	9.1112	6.8092	4.512
6.3	32.1210	29.8184	27.5158	25.2133	22.9107	20.6081	18.3055	16.0029	13.7003	11.3978	9.0952	6.7932	4.496
6.4	32.1053	29.8027	27.5001	25.1975	22.8949	20.5923	18.2898	15.9872	13.6846	11.3820	9.0795	6.7775	4.480
6.5	32.0898	29.7872	27.4846	25.1820	22.8794	20.5768	18.2742	15.9717	13.6691	11.3665	9.0640	6.7620	4.465
6.6	32.0745	29.7719	27.4693	25.1667	22.8641	20.5616	18.2590	15.9564	13.6538	11.3512	9.0487	6.7467	4.450
6.7	32.0595	29.7569	27.4543	25.1517	22.8491	20.5465	18.2439	15.9414	13.6388	11.3362	9.0337	6.7317	4.435
6.8	32.0446	29.7421	27.4395	25.1369	22.8343	20.5317	18.2291	15.9265	13.6240	11.3214	9.0189	6.7169	4.420
6.9	32.0300	29.7275	27.4249	25.1223	22.8197	20.5171	18.2145	15.9119	13.6094	11.3608	9.0043	6.7023	4.405
7.0	32.0156	29.7131	27.4105	25.1079	22.8053	20.5027	18.2001	15.8976	13.5950	11.2924	8.9899	6.6879	4.391
7.1	32.0015	29.6989	27.3963	25.0937	22.7911	20.4885	18.1860	15.8834	13.5808	11.2782	8.9757	6.6737	4.377
7.2	31.9875	29.6849	27.3823	25.0797	22.7771	20.4746	18.1720	15.8694	13.5668	11.2642	8.9617	6.6598	4.363
7.3	31.9737	29.6711	27.3685	25.0659	22.7633	20.4608	18.1582	15.8556	13.5530	11.2504	8.9479	6.6460	4.350
7.4	31.9601	29.6575	27.3549	25.0523	22.7497	20.4472	18.1446	15.8420	13.5394	11.2368	8.9343	6.6324	4.336
7.5	31.9467	29.6441	27.3415	25.0389	22.7363	20.4337	18.1311	15.8286	13.5260	11.2234	8.9209	6.6190	4.323
7.6	31.9334	29.6308	27.3282	25.0257	22.7231	20.4205	18.1179	15.8153	13.5127	11.2102	8.9076	6.6057	4.310
7.7	31.9203	29.6178	27.3152	25.0126	22.7100	20.4074	18.1048	15.8022	13.4997	11.1971	8.8946	6.5927	4.297
7.8	31.9074	29.6048	27.3023	24.9997	22.6971	20.3945	18.0919	15.7893	13.4868	11.1842	8.8817	6.5798	4.284
7.9	31.8974	29.5921	27.2895	24.9869	22.6844	20.3818	18.0792	15.7766	13.4740	11.1714	8.8689	6.5671	4.271
8.0	31.8821	29.5795	27.2769	24.9744	22.6718	20.3692	18.0666	15.7640	13.4614	11.1589	8.8563	6.5545	4.259
8.1	31.8697	29.5671	27.2645	24.9619	22.6594	20.3568	18.0542	15.7516	13.4490	11.1464	8. 8439	6.5421	4.246
8.2	31.8574	29.5548	27.2523	24.9497	22.6471	20.3445	18.0419	15.7393	13.4367	11.1342	8.8317	6.5298	4.234
8.3	31.8453	29.5427	27.2401	24.9375	22.6350	20.3324	18.0298	15.7272	13.4246	11.1220	8.8195	6.5177	4.222
8.4	31.8333	29.5307	27.2282	24.9256	22.6230	20.3204	18.0178	15.7152	13.4126	11.1101	8.8076	6.5057	4.210
8.5	31.8215	29.5189	27.2163	24.9137	22.6112	20.3086	18.0060	15.7034	13.4008	11.0982	8.7957	6.4939	4.199
8.6	31.8098	29.5072	27.2046	24.9020	22.5995	20.2969	17.9943	15.6917	13.3891	11.0865	8.7840	6.4822	4.187
8.7	31.7982	29.4957	27.1931	24.8905	22.5879	20.2853	17.9827	15.6801	13.3776	11.0750	8.7725	6.4707	4.175

8.8	31.7868	29.4842	27.1816	24.8790	22.5765	20.2739	17.9713	15.6687	13.3661	11.0635	8.7610	6.4592	4.164
8.9	31.7755	29.4729	27.1703	24.8678	22.5652	20.2626	17.9600	15.6574	13.3548	11.0523	8.7497	6.4480	4.153
9.0	31.7643	29.4618	27.1592	24.8566	22.5540	20.2514	17.9488	15.6462	13.3437	11.0411	8.7386	6.4368	4.142
9.1	31.7533	29.4507	27.1481	24.8455	22.5429	20.2404	17.9378	15.6352	13.3326	11.0300	8.7275	6.4258	4.131
9.2	31.7424	29.4398	27.1372	24.8346	22.5320	20.2294	17.9268	15.6243	13.3217	11.0191	8.7166	6.4148	4.120
9.3	31.7315	29.4290	27.1264	24.8238	22.5212	20.2186	17.9160	15.6135	13.3109	11.0083	8.7058	6.4040	4.109
9.4	31.7208	29.4183	27.1157	24.8131	22.5105	20.2079	17.9053	15.6028	13.3002	10.9976	8.6951	6.3934	4.099
9.5	31.7103	29.4077	27.1051	24.8025	22.4999	20.1973	17.8948	15.5922	13.2896	10.9870	8.6845	6.3828	4.088
9.6	31.6998	29.3972	27.0946	24.7920	22.4895	20.1869	17.8843	15.5817	13.2791	10.9765	8.6740	6.3723	4.078
9.7	31.6894	29.3868	27.0843	24.7817	22.4791	20.1765	17.8739	15.5713	13.2688	10.9662	8.6637	6.3620	4.068
9.8	31.6792	29.3766	27.0740	24.7714	22.4688	20.1663	17.8637	15.5611	13.2585	10.9559	8.6534	6.3517	4.057
9.9	31.6690	29.3664	27.0639	24.7613	22.4587	20.1561	17.8535	15.5509	13.2483	10.9458	8.6433	6.3416	4.047

5

Well Hydraulics

PROBLEM 29 Time-drawdown data shown in Table 29.1 of an observation well is located at a distance of 100 m (Figure 29.1) from a well discharging 2,500 m^3/day. Thickness of the aquifer is 30 m. Determinate the transmissivity, storativity and hydraulic conductivity of the aquifer, using (a) Theis's, (b) Jacob's, and (b) Chow's methods.

Key Concept Aquifer test (or pumping test) is conducted to estimate the hydraulic properties of aquifers, to evaluate the well performance and to identify the aquifer boundaries, which is for the evaluation of an aquifer by stimulating the aquifer through constant pumping, and observing the aquifer's response (drawdown) in the observation wells. The hydraulic properties of the confined aquifers like transmissivity, hydraulic conductivity and storativity (storage coefficient) can be estimated using Theis's, Jacob's and Chow's methods.

Data of the given problem

TABLE 29.1 Time-drawdown Data

Time since pumping started (min)	*Drawdown* (m)	*Time since pumping started* (min)	*Drawdown* (m)
4	0.24	80	1.86
6	0.50	100	1.98
9	0.70	120	2.08
15	0.98	150	2.20
20	1.12	200	2.34
30	1.34	300	2.56
40	1.50	400	2.70
50	1.60	600	2.92

Distance between two wells = 100 m

Discharge of the well = 2,500 m^3/day

Thickness of the aquifer = 30 m

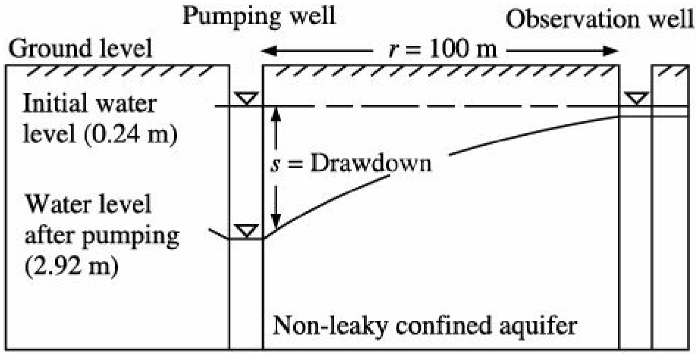


FIGURE 29.1 Pumping well and observation well

Solution

The relevant equations for the estimation of transmissivity, hydraulic conductivity and storativity is shown in Table 29.2 using the Theis's, Jacob's and Chow's methods.

TABLE 29.2 Equations of the Theis's, Jacob's and Chow's Methods

	Theis's method	*Jacob's method*	*Chow's method*
$T =$	$\frac{Q}{4\pi s}W(u)$	$\frac{2.303Q}{4\pi\Delta s}$	$\frac{Q}{4\pi\Delta s_A}W(u)_A$
$S =$	$\frac{u4Tt}{r^2}$	$\frac{2.25Tt_o}{r^2}$	$\frac{u_A 4Tt_A}{r^2}$
$F(u) =$	–	–	$\frac{s_A}{\Delta s_A}$
$K =$	$\frac{T}{b}$	$\frac{T}{b}$	$\frac{T}{b}$

where,

T = transmissivity (m^2/day)

Q = well discharge (m^3/day)

S = storativity (dimensionless)

r = distance between the wells (m)

K = hydraulic conductivity (m/day)

b = aquifer thickness (m)

$W(u)$ or $W(u)_A$ = well function of u

u or u_A = argument of the well $\left(\frac{r^2S}{4Tt}\right)$

s or Δs or Δs_A = drawdown (m)
t or t_o or t_A = time since pumping started (min)
$F(u)$ = function of Chow

Theis's method (1935): The first step in this method is to plot the time (t, min) since pumping started on x-axis and the drawdown (s, m) on y-axis [Figure 29.2(a)] on a trace paper, which is superposed on double logarithmic graph. The second step is to superpose the data of the trace paper on the theoretical (type) curve [Figure 29.2(b)] without any deviation in the coordinate axes of the two papers being held parallel and moved to a position that best fits the type curve [Figure 29.2(c)]. Then, fix the match point (+) and its positions on coordinates [$W(u)$, $1/u$, s and t] are recorded. These values are then used in the equations to calculate T, S and K.

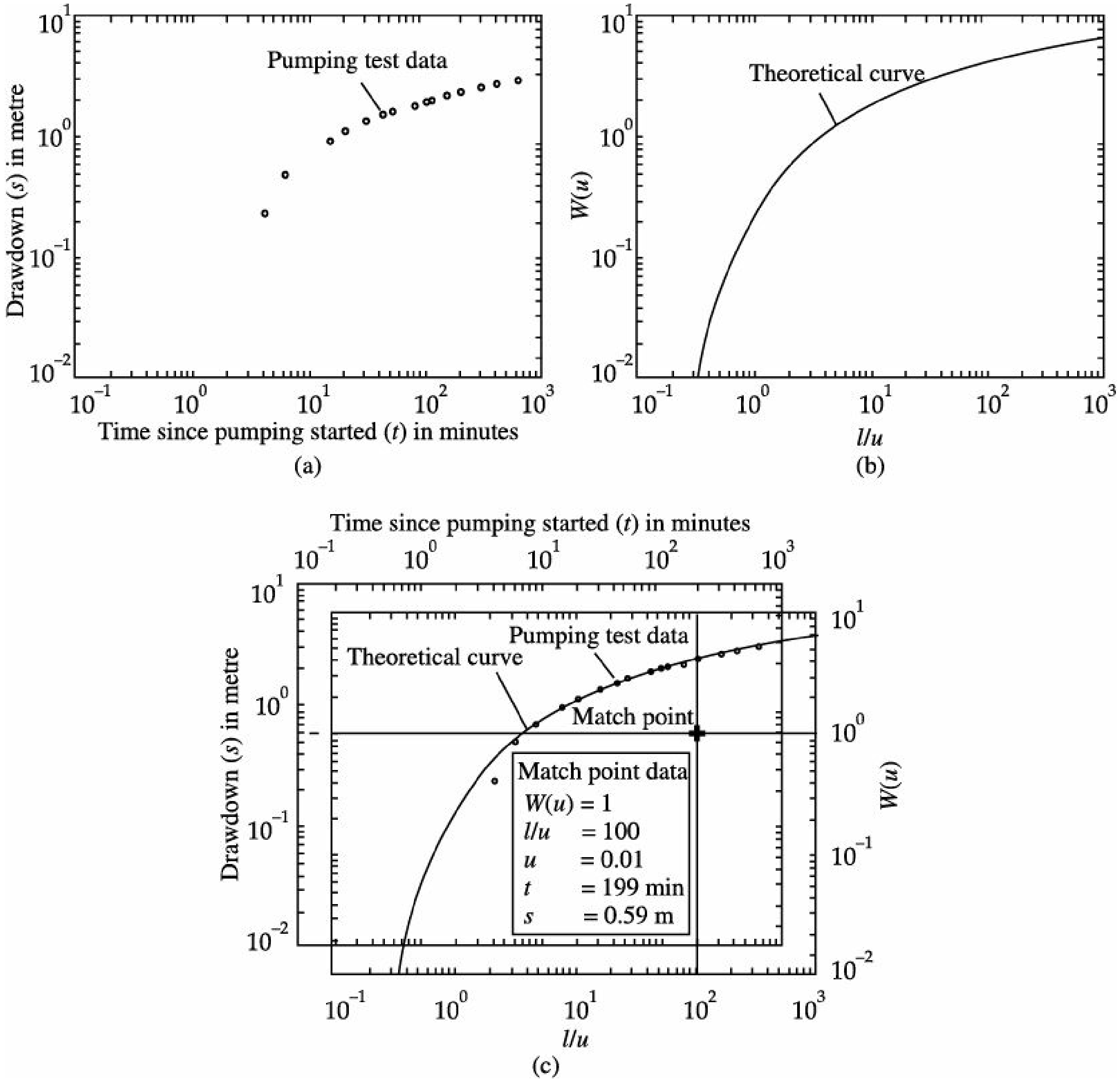


FIGURE 29.2 (a) Plotting of pumping test data on trace paper, following a double logarithmic graph, (b) Theis type (theoretical) curve, and (c) Matching of time-drawdown data with the type curve.

Jacob's method (1946): In this method, the first step is to plot the time (*t*, min) since pumping started on *x*-axis and the drawdown (*s*, m) on *y*-axis in a semi-logarithmic graph (Figure 29.3). In the second step, the straight line is drawn passing through all the plotted points in the graph. The straight line is extrapolated to intercept the zero drawdown axis. The intercepting zero drawdown axis point is designated as t_o. The drawdown (Δs) for one log cycle is recorded. These values are then used to calculate *T*, *S* and *K*.

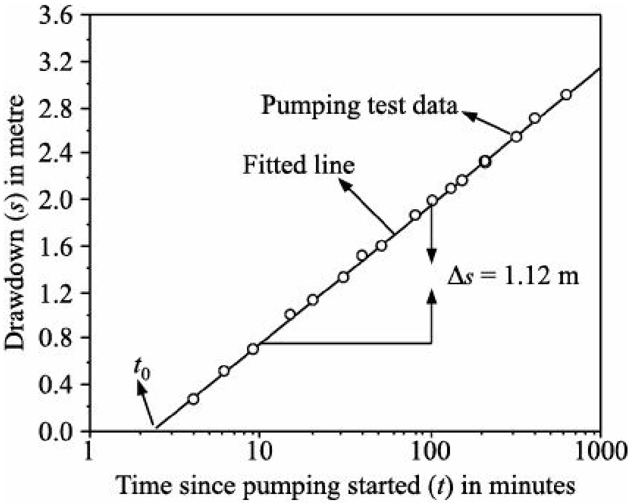


FIGURE 29.3 Plotting of time-drawdown data in Jacob's method.

Chow's method (1952): The first step in this method is to plot the time (t, min) since pumping started is on x-axis and the drawdown (s, min) on y-axis in a semi-logarithmic graph (Figure 29.4). The second step is to select the tangency point (A) on the plotted points and draw a tangent line passing through all the tangency points. The third step is to read the coordinate values for the tangency point, drawdown value (s_A) on the y-axis and t_A on the x-axis, and also the Δs_A per one log cycle of time (t). The fourth step is to calculate $F(u)$ for the tangency point from $F(u) = s_A/\Delta s_A$. The fifth step is to read the values of $W(u)$ and u for the value of $F(u)$ from the nomogram or from the values of Chow's method, of analysis (Figure 29.5 and Table 29.3), and substitute them along with the values of t_A and s_A in Theis's equation to calculate T, S and K.

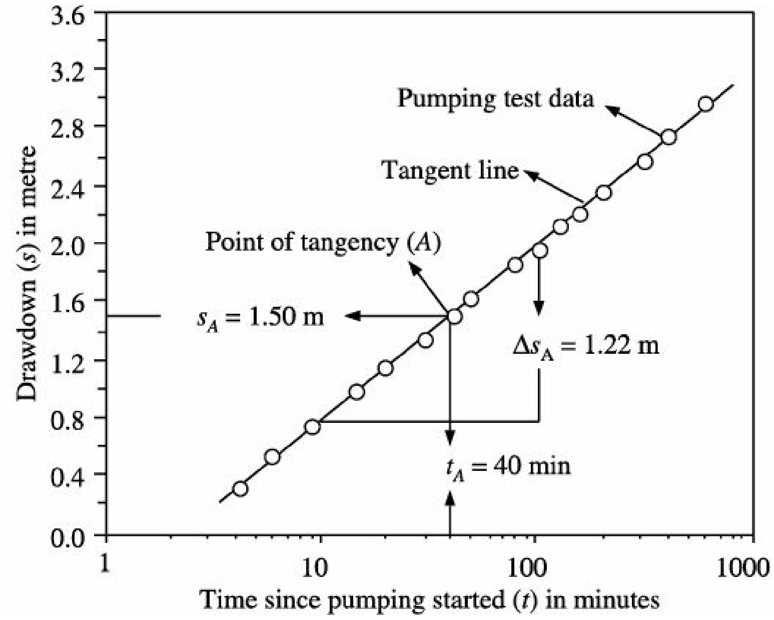


FIGURE 29.4 Plotting of time-drawdown data in Chow’s method.

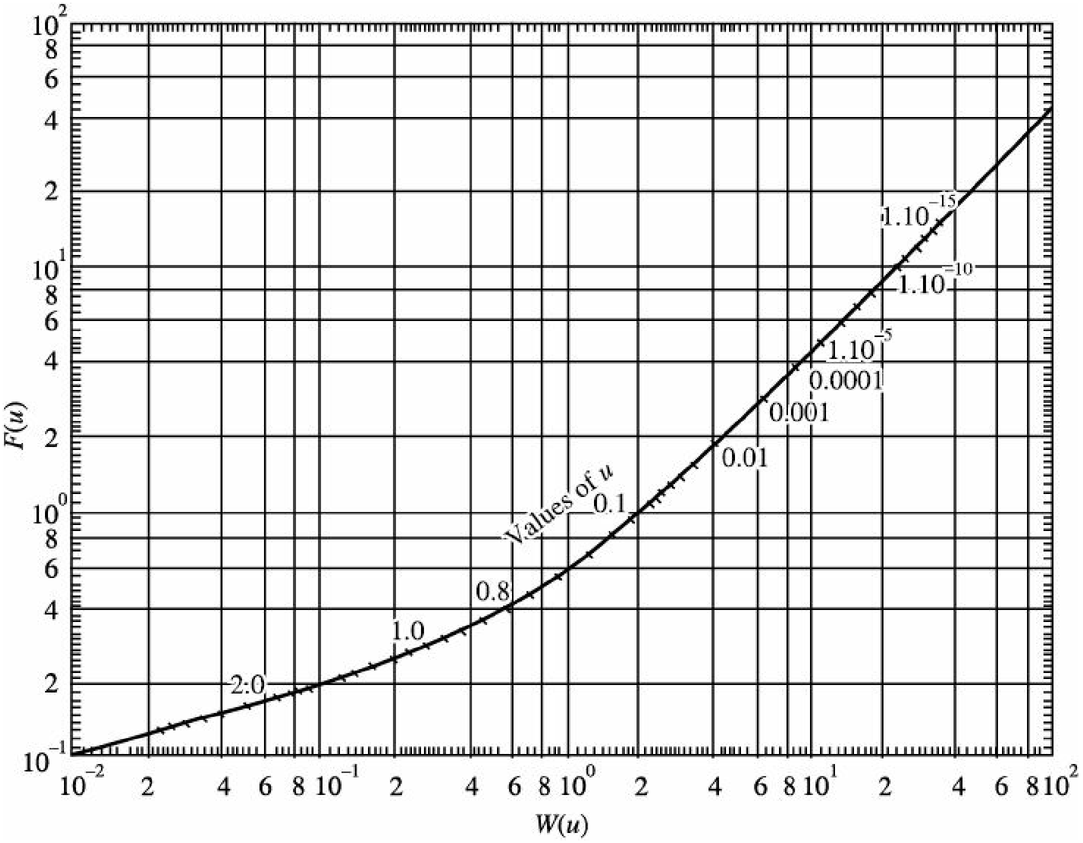


FIGURE 29.5 Chow’s nomogram showing the relation between *u*, *W*(*u*) and *F*(*u*).

TABLE 29.3 Values of *u*, *W*(*u*) and *F*(*u*) for Chow’s Method of Analysis

u	*W*(*u*)	*F*(*u*)	*u*	*W*(*u*)	*F*(*u*)	*u*	*W*(*u*)	*F*(*u*)

5 × 10°	1.14×10^{-3}	7.34×10^{-2}	9×10^{-3}	1.92	9.13×10^{-1}	9×10^{-4}	6.44	
4	3.78	8.98	8	2.03	9.56	8	6.55	
3	1.30×10^{-3}	1.17×10^{-1}	7	2.15	1.00×10^{0}	7	6.69	
2	4.89	1.57	6	2.30	1.06	6	6.84	
1	2.19×10^{-1}	2.59	5	2.47	1.13	5	7.02	
			4	2.68	1.21	4	7.25	
9×10^{-1}	2.60	2.76	3	2.96	1.33	3	7.53	
8	3.11	3.01	2	3.55	1.49	2	7.94	
7	3.74	3.27	1	4.04	1.77	1	8.63	$F(u) = W(u)/2.30$
6	4.54	3.60						
5	5.60	4.01	9×10^{-3}	4.14	1.82	9×10^{-5}	8.74	
4	7.02	4.55	8	4.26	1.87	8	8.86	
3	9.06	5.32	7	4.39	1.92	7	8.99	
2	1.22 × 10°	6.47	6	4.54	1.99	6	9.14	
1	1.80	8.74	5	4.73	2.07	5	9.33	
			4	4.95	2.16			
			3	5.23	2.28			
			2	5.64	2.46			
			1	6.33	2.75			

TABLE 29.4 Results of Pumping Test Analyses (Figs. 29.2 to 29.4)

Theis's method From Figure 29.1	*Jacob's method From Figure 29.3*	*Chow's method From Figure 29.4*
$W(u) = 1$	—	$W(u) = 3$
$1/u = 100$	—	—
$u = 0.01$	—	$u = 0.07$
$t = 199$ min	$t_o = 2.5$ min	$t_A = 40$ min
$s = 0.59$ m	$\Delta s = 1.12$ m	$s_A = 1.50$ m
—	—	$\Delta s_A = 1.22$ m
—	—	$F(u) = \frac{1.50}{1.22} = 1.23$
$T = \frac{2{,}500 \times 1}{4 \times 3.14 \times 0.59}$	$T = \frac{2.303 \times 2{,}500}{4 \times 3.14 \times 1.12}$	$T = \frac{2{,}500 \times 3}{4 \times 3.14 \times 1.50}$
$T = 337.36$ m^2/day	$T = 409.29$ m^2/day	$T = 398.09$ m^2/day
$S = \frac{0.01 \times 4 \times 337.36 \times 199}{100 \times 100 \times 1{,}440}$	$S = \frac{2.25 \times 409.29 \times 2.5}{100 \times 100 \times 1{,}440}$	$S = \frac{0.07 \times 4 \times 398.09 \times 40}{100 \times 100 \times 1{,}440}$
$S = 1.86 \times 10^{-4}$	$S = 1.60 \times 10^{-4}$	$S = 3.10 \times 10^{-4}$

$K = \frac{337.36}{30}$	$K = \frac{409.29}{30}$	$K = \frac{398.09}{30}$
$K = 11.15$ m/day	$K = 13.64$ m/day	$K = 13.27$ m/day

PROBLEM 30 A production well is allowed to recuperate after 20 minutes of uniform pumping rate of 2,600 m^3/day. Time-residual drawdown data are given in Table 30.1. Compute the transmissivity of the aquifer using Theis' recovery method.

Key Concept After pumping is stopped, the water level rises and approaches the initial water level (static water level) observed before pumping began. During the water level recovery, the distance between the water level and the initial water level is called *residual drawdown* (Figure 30.1). The time-residual drawdown data helps to estimating the transmissivity of the aquifer using Theis's recovery method.

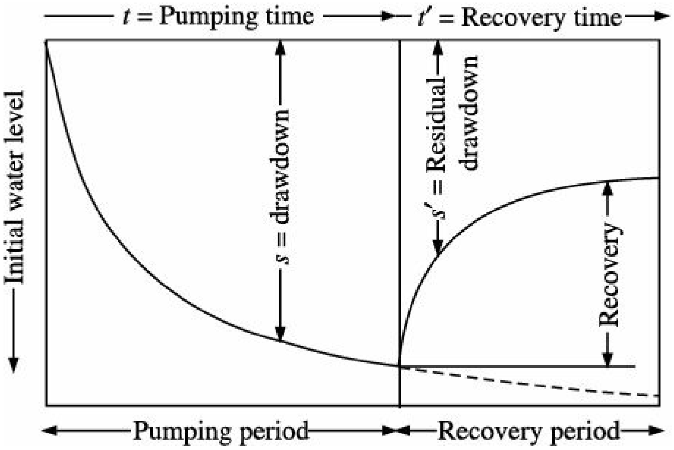


FIGURE 30.1 Residual drawdown.

Data of the given problem

TABLE 30.1 Time-residual Drawdown Data

Time since pumping stopped (min)	*Residual drawdown* (m)
0.5	0.90
0.3	0.78
0.5	0.70
1.0	0.55
2.0	0.45
3.0	0.38

5.0	0.28
10.0	0.20
20.0	0.05

Pumping rate = 2,600 m^3/day
Pumping time = 20 min

Solution

Theis's recovery method (1935): Time since pumping stopped (t/t', min) is plotted on x-axis and residual drawdown (s', m) on y-axis in a semi-logarithmic graph (Figure 30.2). The straight line is drawn passing through all the plotted points. One log cycle is chosen from the graph to select a value of drawdown ($\Delta s'$), and then, this value is used to calculate T.

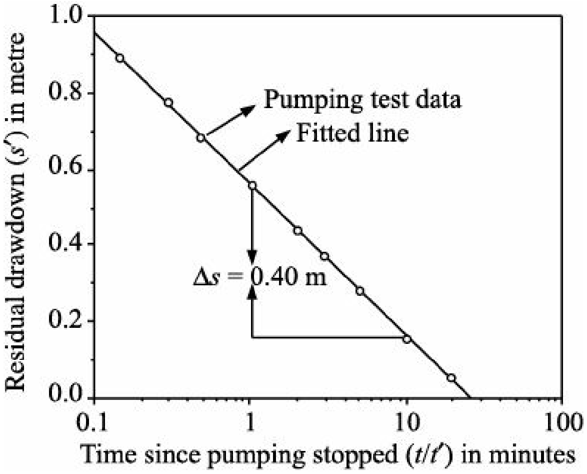


FIGURE 30.2 Plotting of time-residual drawdown data in Theis's recovery method.

$$\text{Transmissivity } (T) = \frac{2.303}{4\pi\Delta s'} \tag{30.1}$$

where,

Q = pumping rate (m^3/day)
$\Delta s'$ = residual drawdown (m)

Therefore,
$$T = \frac{2.303 \times 2{,}600}{4 \times 3.14 \times 0.40} = 1{,}191.84 \text{ m}^2\text{/day}$$

PROBLEM 31 Time-drawn data of a pumping test conducted in a large diameter open well is given in Table 31.1. The radius of the well is 1.75 m. If the constant discharge of the well is 1.15 m^3/min, determine the (a) transmissivity and (b) storativity of the aquifer material using Papadopulos-Cooper's method.

Key Concept Large diameter wells dug down to the water-bearing strata are known as *open wells* (Figure 31.1), which derive water from the formations close to the ground surface. Thus, the wells are always shallow. The large size of the wells allows the storage of large quantities of water in the well. The side walls of the wells are lined with stone masonry so that the water finds entry into the well only from the bottom. When the pumping is not taking place, the water level in the well is the same as the general water table level in the surroundings of the well. When the pumping takes place, the water level in the well is depressed and the difference of the water level in the well is known as *depression head*. For determining the hydraulic properties (transmissivity and storativity) of non-leaky confined aquifers, a mathematical solution of Papadopulos and Cooper is widely used.

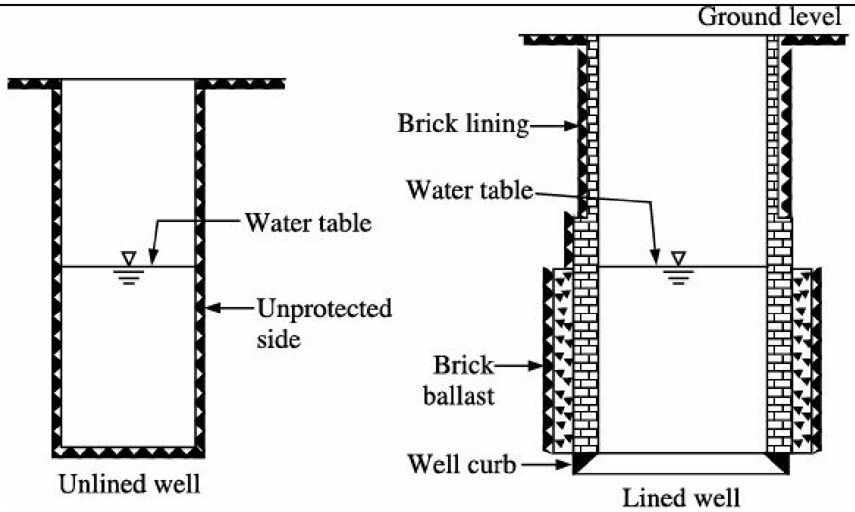


FIGURE 31.1 Open wells.

Data of the given problem

Radius of the well = 1.75 m

Discharge of the well = 1.15 m^3/min

TABLE 31.1 Time-drawdown Data of a Large Diameter Well

Time since pumping started (min)	*Drawdown* (m)
3	0.16
6	0.24
10	0.29
20	0.36
30	0.39

50	0.43
100	0.45
200	0.49

Solution

Papadopulos–Cooper’s method (1963)

(a) $$\text{Transmissivity } (T) = \frac{Q}{4\mu s} F(u_w, \alpha) \tag{31.1}$$

(b) $$\text{Storativity } (S) = \frac{4Ttu_w}{r_w^2} \tag{31.2}$$

or $$u_w = \frac{r_w^2 S}{4Tt} \tag{31.3}$$

where,

Q = well discharge (m^3/min)

$F(u_w, \alpha)$ = function for which numerical values are shown in Figure 31.2, Table 31.2

s = drawdown (m)

t = time (min) since pumping started

r_w = effective radius of the well screen (m^2)

Time (t, min) since pumping started is plotted on x-axis and drawdown (s, m) is plotted on y-axis on a trace paper, which is superposed on a double logarithmic graph [Figure 31.2(a)]. Figure 31.2(b) shows the Papadopulos–Cooper type curve. The trace paper is superposed on the type curve without any deviation in the coordinate axes of the two papers being held parallel and moved to a position that best fits the type curve [Figure 31.2(c)]. Then, the match point (+) is fixed and its positions on coordinates (Fu_w, α, 1/u, s and t) are recorded. These values are then used to calculate T and S.

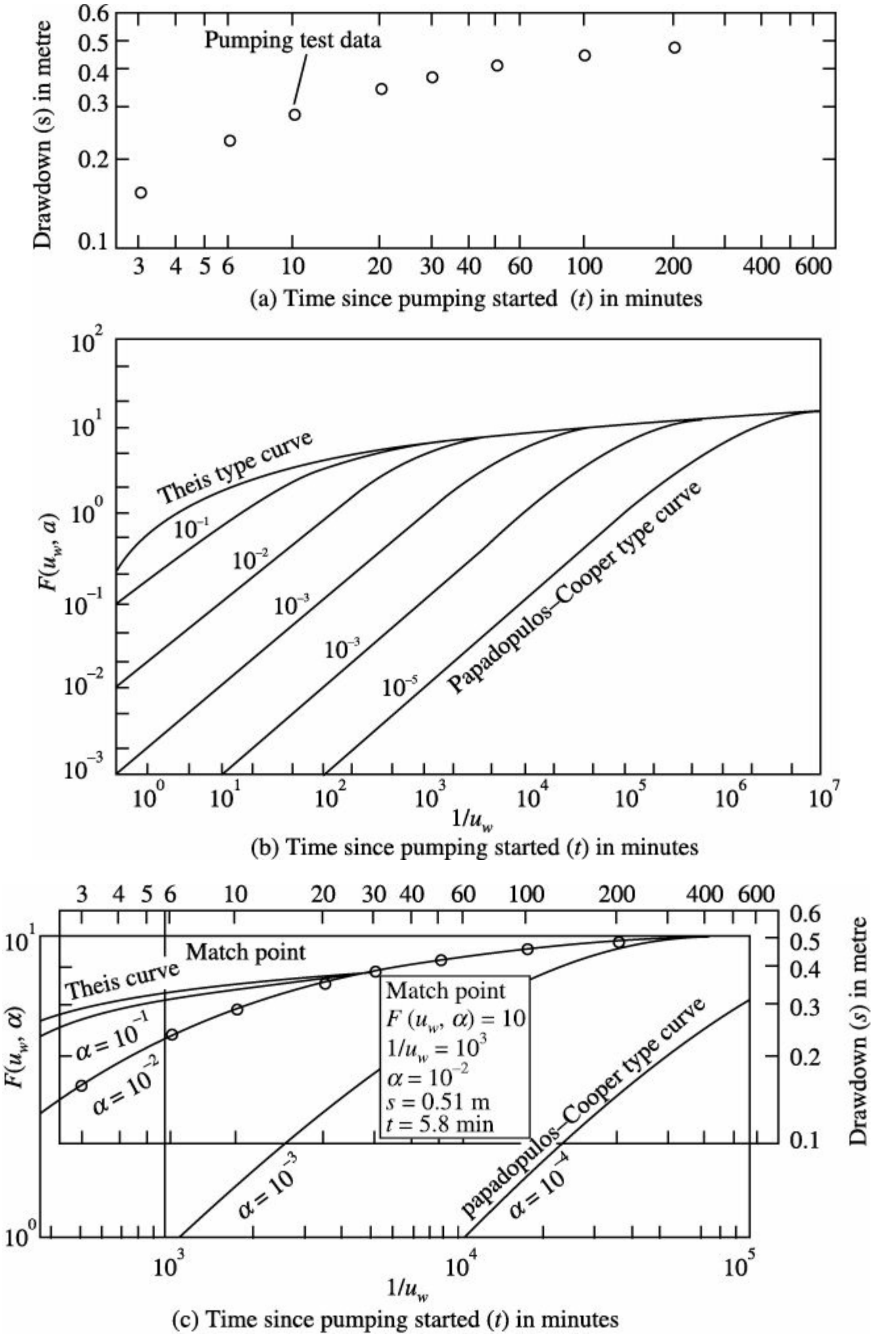


FIGURE 31.2 (a) Plotting of time-drawdown data, (b) Papadopulos–Cooper type curve, and (c) Matching of time-drawdown data with the type curve.

Therefore,
$$T = \frac{1.15 \times 1,440 \times 10}{4 \times 3.14 \times 0.51} = 2,585.24 \text{ m}^2\text{day}$$

Therefore,
$$S = \frac{4 \times 2,585.24 \times 5.8 \times 10^{-3}}{1.75^2 \times 1,440} = 0.04$$

TABLE 31.2 Values of the Function $F(u_w, \alpha)$ for Papadopulos–Cooper of Analysis

$1/u_w$	α = ۱۰$^{-1}$	α = ۱۰$^{-2}$	α = ۱۰$^{-3}$	α = ۱۰$^{-4}$	α = ۱۰$^{-5}$
1×10^{-1}	9.75×10^{-3}	9.98×10^{-4}	1.00×10^{-4}	1.00×10^{-5}	1.00×10^{-6}
1×10^{0}	9.19×10^{-2}	9.91×10^{-3}	9.99	1.00×10^{-4}	1.00×10^{-5}
2	1.77×10^{-1}	1.97×10^{-2}	2.00×10^{-3}	2.00	2.00
5	4.06	4.89	4.99	5.00	5.00
1×10^{1}	7.34	9.66	9.97	1.00×10^{-3}	1.00×10^{-4}
2	1.26×10^{0}	1.90×10^{-1}	1.99×10^{-2}	2.00	2.00
5	2.30	4.53	4.95	4.99	5.00
1×10^{2}	3.28	8.52	9.83	9.98	1.00×10^{-3}
2	4.25	1.54×10^{0}	1.99×10^{-1}	1.00×10^{-2}	2.00
5	5.42	3.04	4.72	4.97	5.00
1×10^{3}	6.21	4.54	9.07	9.90	9.99
2	6.96	6.03	1.69×10^{0}	1.96×10^{-1}	2.00×10^{-2}
5	7.87	7.56	3.52	4.81	4.98
1×10^{4}	8.57	8.44	5.53	9.34	9.93
2	9.32	9.23	7.63	1.77×10^{0}	1.97×10^{-1}
5	1.02×10^{1}	1.02×10^{1}	9.68	3.83	4.86
1×10^{5}	1.09	1.09	1.07×10^{1}	6.24	9.49
2	1.16	1.16	1.15	8.89	1.82×10^{0}
5	1.25	1.25	1.25	1.17×10^{1}	4.03
1×10^{6}	1.32	1.32	1.32	1.29	6.78
2	1.39	1.39	1.39	1.38	1.01×10^{1}
5	1.48	1.48	1.48	1.48	1.37
1×10^{7}	1.55	1.55	1.55	1.55	1.51
2	1.62	1.62	1.62	1.62	1.60
5	1.70	1.70	1.70	1.71	1.71
1×10^{8}	1.78	1.78	1.78	1.78	1.78
2	1.85	1.85	1.85	1.85	1.85
5	1.94	1.94	1.94	1.94	1.94
1×10^{9}	2.01	2.01	2.01	2.01	2.01

PROBLEM 32 Drawdown data with a distance of observation well in an area is shown in Table 32.1. The well screen is installed over the whole thickness (25 m) of the medium sand aquifer material. A discharge of 3,000 m^3/day is pumped for 12 hours till the drawdown becomes steady. Estimate the (a) transmissivity and (b)

hydraulic conductivity of the aquifer material using numerical and graphical methods.

Key Concept The data on drawdown is collected from an observation well located at different distances for computation of the (leaky) aquifer characteristics of transmissivity and hydraulic conductivity using numerical and graphical methods.

Data of the given problem

TABLE 32.1 Drawdown at Observation Well

Drawdown (m)	*Observation well at a distance* (m)
1.8	1.5
1.0	25
0.7	75

Thickness of the aquifer material = 25 m

Drawdown in observation well = 1.8, 1.0 and 0.7 m at distances of 1.5 m, 25 m and 75 m

Discharge = 3,000 m^3/day

Solution

Numerical method: Calculations of transmissivity and hydraulic conductivity using numerical method are as follows:

(a) *Transmissivity* (*T*): It is the rate of flow under a unit hydraulic gradient through a unit width of aquifer of thickness [Eq. (32.1)], which is expressed in square metre per day (m^2/day).

$$\text{Discharge } (Q) \text{ (Thiem's formula, 1906)} = \frac{2\pi Kb(s_1 - s_2)}{2.30 \log\left(\dfrac{r_2}{r_1}\right)} \tag{32.1}$$

$$\text{Then,} \qquad T \text{ or } Kb = \frac{2.30Q}{2\pi(s_1 - s_2)} \log\frac{r_2}{r_1} \tag{32.2}$$

where,

Kb = transmissivity (m^2/day)

b = thickness of the aquifer (m)

Q = well discharge (m^3/day)

s_1 and s_2 = steady state drawdown (m) in the piezometers located at distances of r_1 and r_2

r_1 and r_2 = distances (m) of two piezometers from the pumped well

Therefore,

$$T = \frac{2.30 \times 3{,}000}{2 \times 3.14(1.0 - 0.7)} \times \log \frac{75}{25}$$

$$T = 1{,}746.97 \ \text{m}^2/\text{day}$$

(b) *Hydraulic conductivity* (K)*:* It is the rate of flow under a unit hydraulic gradient through a unit cross-sectional area of an aquifer [Eq. (32.3)] and is expressed in m/day.

$$K = \frac{T}{b} \tag{32.3}$$

Therefore,

$$K = \frac{1{,}746.96}{25} = 69.88 \ \text{m/day}$$

Graphical method: The transmissivity and hydraulic conductivity can also be computed by plotting the values of distance (r, m) between the pumped well and observation well on x-axis and drawdown (s, m) on y-axis on a simple logarithmic paper (Figure 32.1), following Thiem's method. The straight line is drawn passing through all the plotted points. The drawdown (s_s) of one log cycle is recorded.

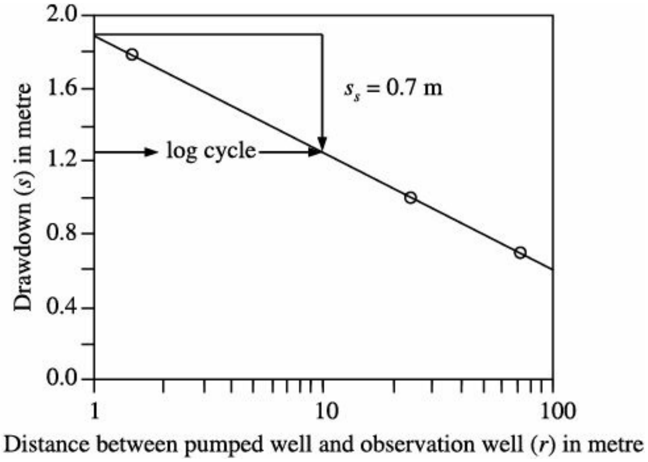


FIGURE 32.1 Plotting of distance between the pumped well and observation well versus drawdown following Thiem's method.

(a)
$$\text{Discharge } (Q) = \frac{2\pi Kb}{2.30}\Delta s \tag{32.4}$$

Then,
$$Kb \quad \text{or} \quad \text{Transmissivity } T = \frac{2.30Q}{2\pi\Delta s} \tag{32.5}$$

where,

Δs = drawdown (m) observed from the graph

Therefore,
$$T = \frac{2.30 \times 3{,}000}{2 \times 3.14 \times 0.7}$$
$$T = 1{,}569.61 \text{ m}^2/\text{day}$$

(b)
$$\text{Hydraulic conductivity } (K) = \frac{T}{b}$$

Therefore,
$$K = \frac{1{,}569.61}{25}$$
$$= 62.78 \text{ m/day}$$

PROBLEM 33 A dug well of 3 m diameter tapping the weathered rock of 5 m thickness records a total drawdown of 1.732 m at the end of 100 min of pumping. The recuperation data of the well is given in Table 33.1. Determine the (a) specific capacity, if the time is 25 and 40 min, using Slichter's method, and (b) yield factor of the rock.

Key Concept From the data of time-residual drawdown of the large diameter dug well, the specific capacity and yield factor can be estimated. The specific capacity of well is an index of well productivity in terms of yielding and transmissivity capacity of the aquifer (clearly, the larger the specific capacity, the better is the well), which is an amount of water that is furnished under unit lowering of the surface of the water in a well by pumping. It decreases with the increase of the pumping rate as well as the prolonged pumping time. Whereas, the yield factor (or yield capacity or specific capacity index) expresses the specific capacity of the well for unit thickness of the aquifer tapped.

Data of the given problem

Diameter of the dug well = 3 m

Radius of the diameter = 1.5 m

Thickness of the weathered rock = 5 m

Total drawdown = 1.732 m

Total pumping time = 100 min

TABLE 33.1 Time-residual Drawdown Data

Time since pump stopped (min)	*Depth to water level* (m bgl)	*Total drawdown* (s_1)	*Residual drawdown, m* (s_2)	$\frac{\textit{Total drawdown } (s_1)}{\textit{Residual drawdown } (s_2)}$	$\log \frac{s_1}{s_2}$
0	6.111	1.732	–	1.000	0
0.5	5.975	–	1.711	1.012	0.0052
10	5.751	–	1.680	1.031	0.0133
20	5.290	–	1.620	1.069	0.0290
30	4.955	–	1.564	1.107	0.0444
50	4.551	–	1.461	1.185	0.0737
100	3.732	–	1.247	1.389	0.1427

Solution

(a) Specific capacity (C) (Slichter's formula, 1906): It is the ratio of the well area and water levels to the pumping time [Eq. (33.1)], which is expressed in cubic metre per minute per metre (m^3/min/m).

$$C = 2.303 \frac{A}{t} \log_{10} \frac{s_1}{s_2} \tag{33.1}$$

where,

C = specific capacity (m^3/min/m)

A = area of the cross section [πr^2, where r is the radius of the diameter $\left(\frac{22}{7} \times 1.5^2 = 7.065\right)$]

t = time (min) since pumping stopped

s_1 = drawdown (m) just before pumping was shut down

s_2 = residual drawdown (m) at any time after pump was shut down

Figure 33.1 shows the plots of time versus log s_1/s_2. The straight line is drawn passing through the plotted points to derive the values of log s_1/s_2 corresponding to the time of 25 min and 40 min. Then, these values are used to compute the specific yield and yield factor.

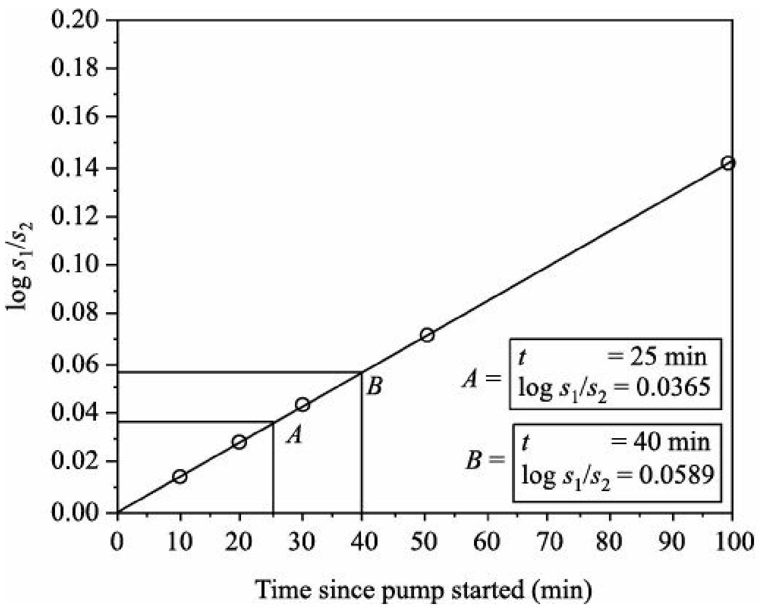


FIGURE 33.1 Plot of time versus log s_1/s_2.

Therefore, $$C \text{ for } A = 2.303 \times \frac{7.065}{25} \times 0.0365 = 0.024 \text{ m}^3/\text{min/m}$$

Therefore, $$C \text{ for } B = 2.303 \times \frac{7.065}{40} \times 0.0589 = 0.024 \text{ m}^3/\text{min/m}$$

$$\text{Average, } C = \frac{0.024 + 0.024}{2} = 0.24 \text{ m}^3/\text{min/m}$$

(b) Yield factor (Q_f): It is also called *specific capacity index*. It is the ratio of specific capacity to aquifer thickness [Eq. (33.2)], which is expressed in cubic metre per minute per metre (m^3/min/m) or in litres/per minute (or lpm) per minute per metre (lpm/min/m).

$$Q_f = \frac{C}{b} \tag{33.2}$$

where,

Q_f = yield factor (lpm/min/m)

b = thickness of the aquifer (m)

Therefore, $$Q_f = \frac{0.024}{5}$$
$$= 0.0048 \text{ lpm/min/m} \quad \text{or} \quad 4.8 \times 10^{-6} \text{ m}^3/\text{min/m}$$

PROBLEM 34 If the discharge, drawdown, hydraulic conductivity, thickness of the aquifer (depth of the cavity) and radius of influence are 0.4 m^3/s, 5 m, 4.2 × 10^{-}

^{4} m/s, 15 m and 145 m, respectively, observed from a cavity well, determine the (a) radius and (b) width of the cavity.

Key Concept Cavity well is a tube well, which, being without strainers, draws its suppliers from one aquifer or water-bearing stratum only (Figure 34.1). It does not go very deep and requires a very hard clayey stratum to form a strong and dependable roof over the cavity. The stratum immediately on the top of the water-bearing stratum, in which the cavity is proposed to be developed, is known as roof of the cavity. The stability of the well and width of the cavity depend on the sharing strength of the clay constituting the roof of the cavity. Thus, it is essential to estimate the radius and width of the cavity.

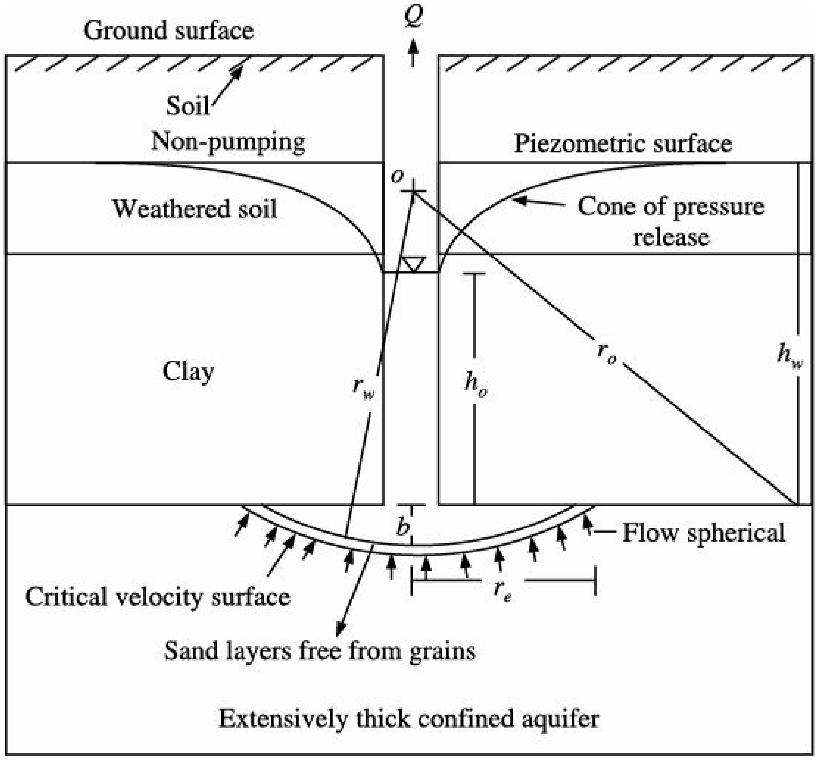


FIGURE 34.1 Cavity well.

Data of the given problem

Discharge (yield) = 0.4 m^3/s

Drawdown = 5 m

Hydraulic conductivity = 4.2×10^{-4} m/s

Thickness of the aquifer = 15 m
Radius of influence = 145 m

Solution

(a) Radius of the cavity (r_w): It expresses the radius from the resting on the top of a confined aquifer to the pumping well centre [Eqs. (34.1) and (34.2)], which is expressed in metre (m).

$$\text{Well yield } (Q) \text{ (Dupuit's formula, 1848)} = \frac{2\pi Kb(h_w - h_o)}{1 - \dfrac{r_w}{r_o}} \tag{34.1}$$

Then,

$$r_w = r_o - \left[\frac{2\pi kb\,(h_w - h_o)}{Q} \times r_o\right] \tag{34.2}$$

where,

K = hydraulic conductivity (m/s)
b = thickness of the aquifer (m)
$h_w - h_o$ = drawdown (m)
r_o = radius of the influence (m)
r_w = radius of the cavity (m)

Therefore,

$$r_w = 145 - \left[\frac{2 \times 3.14 \times 4.2 \times 10^{-4} \times 0.15 \times 5}{0.4} \times 145s\right] = 144.28 \text{ m}$$

(b) Width of the cavity (r_e): It is the root product of radius of the well cavity and thickness of an aquifer [Eq. (34.3)], which is expressed in metre (m).

$$r_e = \sqrt{(2r_w - b)\,b} \tag{34.3}$$

Therefore,

$$r_e = \sqrt{(2 \times 144.28 - 0.15)\,0.15} = 6.58 \text{ m}$$

PROBLEM 35 In an area, 15 flow channels are observed from a flow net analysis of a well. The pumping rate of well is 1,200 m^3/day. Head drop between the successive piezometric contours is 4 m. Thickness of the aquifer is 10 m. Determine the (a) transmissivity and
(b) hydraulic conductivity of the aquifer.

Key Concept The flow fields show almost the square of flow net (Figure 35.1) from the flow lines (stream lines) and equipotential lines (having the same head). Thus, the contour maps of water levels are prepared from the wells and the flow lines, which are drawn to form an orthogonal system of small squares. The flow lines are parallel to an impermeable boundary and they are drawn perpendicular to water level contours. Such water level contour maps with flow lines drawn provide useful information for locating new well sites in terms of the areas of transmissivity or hydraulic conductivity.

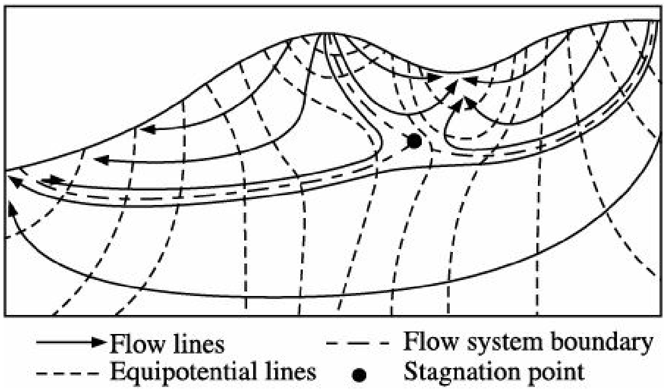


FIGURE 35.1 Flow net analysis.

Data of the given problem

Number of flow channels = 15

Head drop between the successive piezometric contours = 4 m

Thickness of the aquifer = 10 m

Pumping rate or well discharge or yield = 1,200 m^3/day

Solution

(a) Transmissivity (*T*): It is the ratio of the well discharge to the number of flow channels and head drop between the wells [Eq. (35.1)], which is expressed in square metre per day (m^2/day).

$$T = \frac{Q}{n_f h_d} \tag{35.1}$$

where,

Q = well discharge (m^3/day)
n_f = number of flow channels
h_d = head drop between the successive piezometric contours (m)

Therefore, $$T = \frac{1,200}{15 \times 4} = 20 \text{ m}^2/\text{day}$$

(b) Hydraulic conductivity (*K*): It is the ratio of the transmissivity to the thickness of aquifer [Eq. (35.2)] and is expressed in metre per day (m/day).

$$K = \frac{T}{b} \tag{35.2}$$

where,

T = transmissivity (m^2/day)

b = thickness of the aquifer (m)

Therefore, $$K = \frac{20}{10} = 2 \text{ m/day}$$

PROBLEM 36 A deep well contains a casing with radius of 7.3 cm and a screen with radius of 4.9 cm. The water level is at a depth of 9.502 m. Thickness of the aquifer material is 6 m. A slug of 10 l is injected into a well, raising the water level up to 0.60 m. Estimate the (a) transmissivity, (b) hydraulic conductivity and (c) storativity.

Key Concept In the low-permeability materials, the hydraulic conductivity is too small to conduct a pumping test. Thus, an alternative method of testing involves a sudden injecting of a slug of water of known volume (say 10 l) into the well (Figure 36.1). The rate at which the water level falls is controlled by the formation characteristics. This is known as *slug test*. The well casing has a radius r_c and the well screen has a radius r_s. Immediately, after injection, the water level in the well has an elevation (H_o) above the initial head. As the water level falls, the difference (H) in the water level elevation between that at time (t) and that at the original head is measured. This is a method for determination of transmissivity, hydraulic conductivity and storativity.

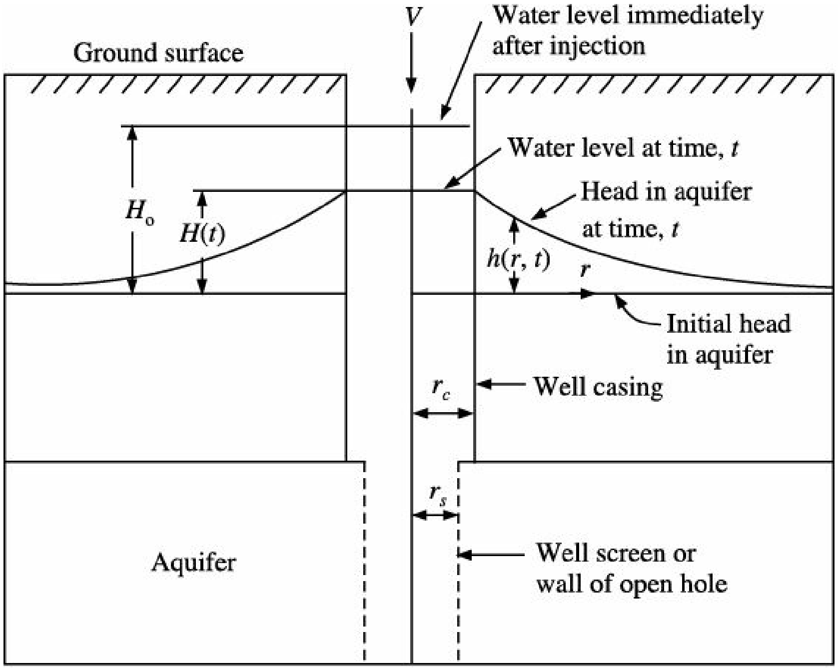


FIGURE 36.1 Slug test.

Data of the given problem

Radius of the well casing = 7.3 cm

Radius of the well screen = 4.9 cm

Depth of the water level = 9.502 m

Introduced slug into the well = 10 l or 0.010 m^3

Injected slug = 10 l

Rise of water level = 0.60 m

TABLE 36.1 Particulars of Residual Head and Elapsed Time

Elapsed time t (*s*)	*Residual head H* (m)	H/H_o
2	0.53	0.89
5.5	0.47	0.78
10	0.41	0.68
28	0.29	0.48
41	0.16	0.27
70	0.08	0.14
140	0.03	0.05

Solution

Head inside the well above the initial head at the instant of injection of slug (H_o): It is the ratio of the amount of injected slug to the effective radius of well casing [Eq. (36.1)].

$$H_o = \frac{V}{\pi r_c^2} \tag{36.1}$$

where,

V = amount of injected slug (m^3)
r_c = effective radius of well casing (cm)

Therefore, $$H_o = \frac{0.010}{3.14 \times 0.073^2} = 0.60$$

(a) To calculate transmissivity, Cooper et al. (1967) and Lohman (1972)'s method is used: A type curve for slug test is shown in Figure 36.2(a). A plot of H/H_o as a function of t is made on semi-logarithmic paper [Figure 36.2(b)]. It is superimposed on the type curve. At the axis for $Tt/r^2 = 1.0$, the value of t_1 is 13 s.

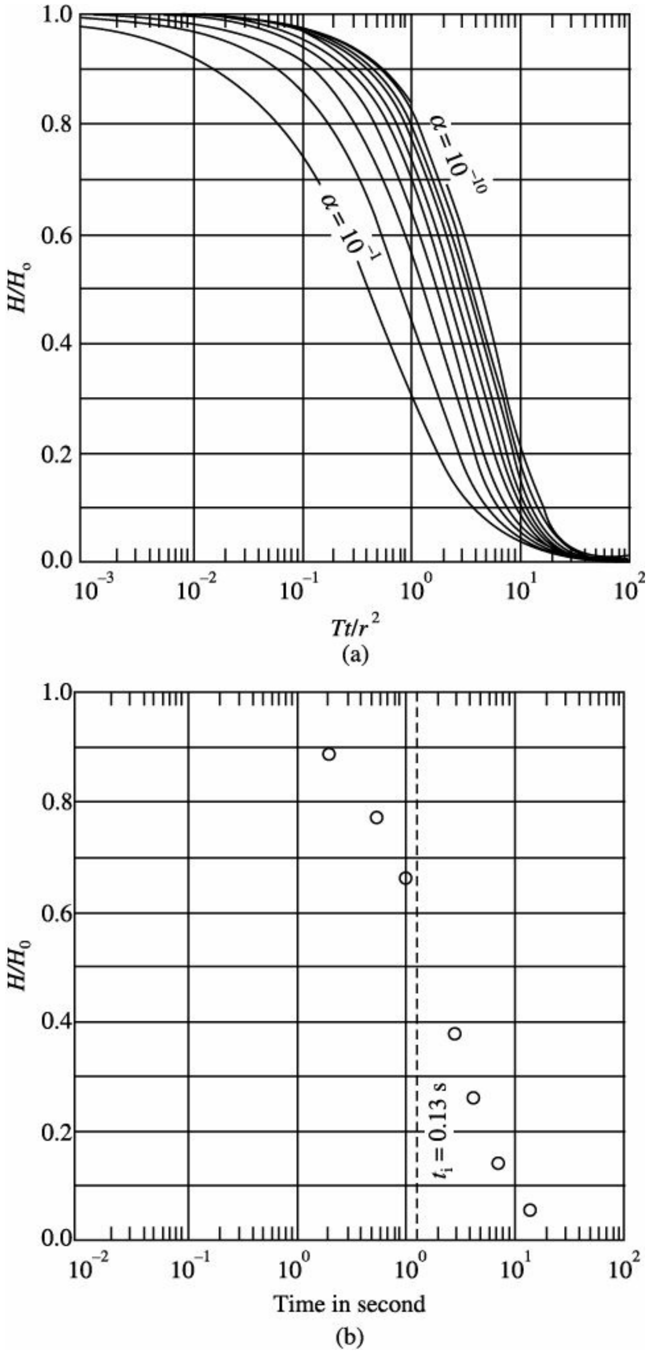


FIGURE 36.2 (a) Type curve for slug test in a well of a finite diameter and (b) field data plot of H/H_o as a function of time for a slug test analysis.

$$\text{Transmissivity } (T) = \frac{1.0 r_c^2}{t_1} \tag{36.2}$$

where,

r_c = radius of the well casing

t_1 = vertical time axis

Therefore, $$T = \frac{1.0 \times 7.3^2}{0.13} = 4.10 \text{ cm}^2\text{/s}$$

(b) Hydraulic conductivity $(K) = \dfrac{T}{b}$ (36.3)

where,

T = transmissivity (cm^2/s)

b = thickness of the aquifer material (m)

Therefore, $$K = \frac{4.10}{600} = 6.83 \times 10^{-3} \text{ cm/s}$$

(c) Storativity $(S) = \dfrac{\alpha r_c^2}{r_s^2}$ (36.4)

where,

$\alpha = 10^{-3}$ [from Figure 39.2(a)]

r_c^2 = radius of the well casing (cm)

r_s^2 = radius of the well screen (cm)

Therefore, $$S = \frac{10^{-3} \times 7.3^2}{4.9^2} \tag{36.5}$$

$$S = 2.22 \times 10^{-3}$$

6

Well Design and Construction

PROBLEM 37 The following data is observed from a grain size distribution curve of an aquifer material. Determine the (a) type of well, (b) slot size of screen, (c) diameter of screen, (d) screen parameter, and (e) well losses (aquifer loss and well loss).

Key Concept The grain size analysis of the aquifer material helps in the selection of well type, slot size of screen, screen diameter, screen parameter, and well losses. The samples of the aquifer material collected from the stratum are taken as a representation of the entire aquifer for the analysis of well design. A proper well design needs an efficient utilisation of aquifer, long service life, low initial cost, low maintenance cost and low operation cost, which depend on the hydrogeological, topographical and climatic conditions.

Data of the given problem

Thickness of the aquifer = 30 m

Median grain size = 0.47 mm

Screen size = 0.51 mm

Effective grain size = 0.23 mm

Effective open area for screen = 7.5% of the gross surface area (15% of the selected screen open area × 50% blockage due to obstruction by aquifer grains

Length of the screen = 25 m

Expected discharge = 1.6 m^3/min or 0.027 m^3/s

Influence of radius = 145 m

Effective radius of well = 0.162

Solution

(a) Type of the well: It is determined as follows:

Uniformity coefficient (C_u)*:* It is an index of grading or particle size distribution of the soil material [Eq. (37.1)]. It is expressed as the ratio of the screen grain size (D_{60}) to the effective grain size (D_{10}).

$$C_u = \frac{D_{60}}{D_{10}} \tag{37.1}$$

where,

D_{60} = screen grain size (mm)
D_{10} = effective grain size (mm)

Therefore, $$C_u = \frac{0.51}{0.23} = 2.22$$

If D_{10} and C_u are less than 0.25 mm and 2.50, respectively, the artificial gravel-packed well can be selected.

Size of the gravel pack: A gravel pack is simply a down-hole filter designed to prevent the production of unwanted formation sand. The formation sand is held in place by properly sized gravel pack sand, which, in turn, is held in place with a properly-sized screen (Figure 37.1).

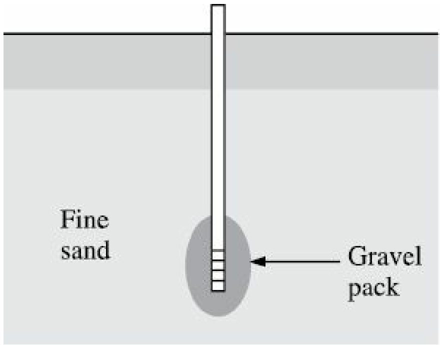


FIGURE 37.1 Gravel pack.

The size of the gravel pack is equal to 4 to 5 times the median grain size (D_{50}) of the aquifer material. Here, the value of D_{50} is 0.47 mm. Thus, the gravel pack varies from 1.88 (0.47 × 4) mm to 2.35 (0.47 × 5) mm. On average, it is 2.12 mm.

(b) Slot size of the screen: A well screen is a filtering device that serves as the intake portion of wells constructed in unconsolidated or semi-consolidated aquifers. The screen permits water to enter the well from the saturated aquifer, prevents sediment from entering the well, and serves structurally to support the aquifer material.

The median grain size D_{50} in the finest sample is less than 4 times the D_{50} size of the material in the coarsest sample. Therefore, the slot size is not selected for individual sample, but it is on the basis of the finest sample. The materials overlying the aquifer will not easily cave so that the screen size (D_{60} = 0.51 mm) can be selected as a proper slot size.

(c) Diameter of the screen (D_s): Selection of the screen diameter depends on the installation of the pump suitable for the desired discharge with the minimum head loss. It is defined as the ratio of expected discharge to optimum screen entrance velocity, effective open area and length of the screen [Eq. (37.2)]. This is expressed in metre (m).

$$D_s = \frac{Q}{V_e \pi A_p L_s} \tag{37.2}$$

where,

Q = expected well discharge (m^3/s)
v_e = optimum screen entrance velocity (cm/s)
A_p = effective open area of the screen (%)
L_s = length of the screen (m)

$$\text{Hydraulic conductivity } (K) \text{ (Allen Hazen's formula, 1905)} = CD_{10}^2 \tag{37.3}$$

where,

C = constant (850; Table 17.1)
D_{10} = effective grain size (mm)

Therefore,
$$K = 850 \times (0.23)^2$$
$$K = 45 \text{ m/day or } 0.052 \text{ m/s}$$

Entrance velocity (V_e), as per the hydraulic conductivity = 2.0 cm/s (Appendix XI)

Therefore,
$$D_s = \frac{0.027}{0.02 \times 3.14 \times 0.075 \times 25}$$
$$D_s = 0.23 \text{ m}$$

(**d) Screen parameter (C_s):** It is the ratio of the slot, velocity, screen length and screen area to screen diameter [Eq. (37.4)].

$$\frac{C_s L_s}{D_s} = \frac{8\sqrt{2}C_c C_v A_p L_s}{D_s} \tag{37.4}$$

where,

C_s = coefficient of screen (dimensionless) $(= 8\sqrt{2}C_c C_v A_p)$
L_s = length of the screen (m)
D_s = diameter of the screen (m)
C_c = coefficient of contraction value for square slots (0.626) (dimensionless)
C_v = coefficient of velocity value (0.97) (dimensionless)
A_p = ratio of slot area to the total area of the screen (dimensionless)

Therefore,
$$C_s = \frac{8\sqrt{2}\times 0.626\times 0.97\times 0.15\times 25}{0.23} = 112$$

The value of the screen parameter is generally more than 60 so that it would not affect the well loss.

(e) Well losses (aquifer loss and well loss): The drawdown in a pumped well consists of two components—the aquifer (formation) losses and the well losses (Figure 37.2). Aquifer losses are the head losses that occur in the aquifer, where the flow is laminar. Well losses are divided into linear and non-linear head losses. Linear well losses are caused by damage to the aquifer during drilling and completion of the well. Non-linear well losses are the friction losses that occur inside the well screen and in the suction pipe, where the flow is turbulent.

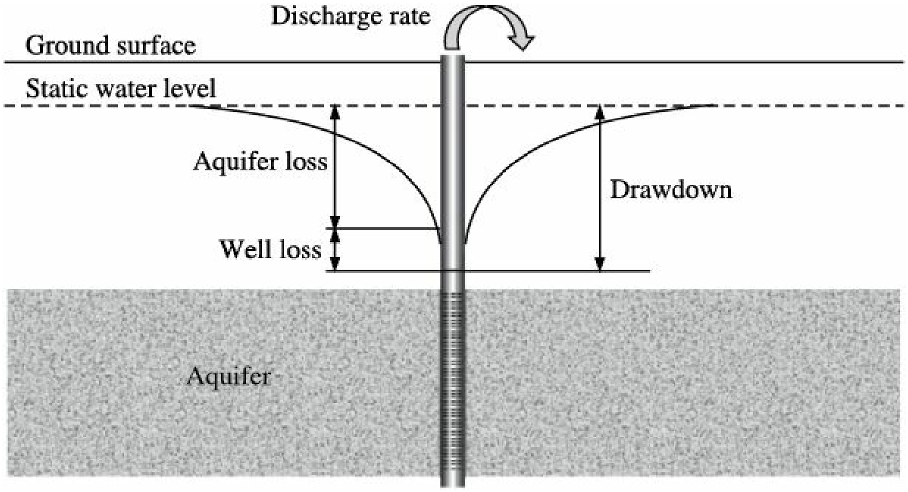


FIGURE 37.2 Head losses in a pumped well.

Aquifer loss (BQ) (Thiem's formula, 1906): It is the ratio of the well discharge and well radius to hydraulic conductivity and aquifer thickness [Eq. (37.5)], which is expressed in metre (m).

$$BQ = \frac{2.30Q \log\left(\frac{r_o}{r_w}\right)}{2\pi Kb} \tag{37.5}$$

where,

Q = well discharge (m^3/day)
r_o = radius of the influence (m)
r_w = effective radius of well (m)
K = hydraulic conductivity (m/s)
b = thickness of aquifer (m)

Therefore, $$BQ = \frac{2.30 \times 0.027 \times \log\left(\frac{145}{0.162}\right)}{2 \times 3.14 \times 5.20 \times 10^{-4} \times 30} = 1.87 \text{ m}$$

Well loss (CQ^2): It is the ratio of well screen and well radius to hydraulic conductivity, screen length and well discharge [Eq. (37.6)], which is expressed in metre (m).

To determine the well loss, it is necessary to calculate the value of $f\frac{L_s}{D_s}$, which is a dimensionless parameter.

where,

f = Darcy–Weisbach resistance coefficient (the value of f is 0.003 for brass, copper and lead; 0.005 for iron and steel; and 0.01 for concrete and riveted steel)

L_s = length of the screen (m)

D_s = diameter of the screen (m)

$$f\frac{L_s}{D_s} = 0.01\frac{25}{0.23} = 1.09$$

Therefore,

$$CQ^2 = \frac{2.30 D_s^4 g \log\left(\frac{r_o}{r_w}\right)}{64\, K L_s Q} \tag{37.6}$$

where,

D_s = diameter of the screen (m)

g = acceleration due to gravity (9.81 m/s^2)

$$\text{So, } CQ^2 = \frac{2.30 \times 0.23^4 \times 9.81 \times \log\left(\frac{145}{0.162}\right)}{64 \times 5.2 \times 10^{-4} \times 25 \times 0.023} = 9.74 \text{ m}$$

As per the values of $f\frac{L_s}{D_s}$ and CQ^2, the ratio $\frac{S_w}{S}$ is 0.025 (Appendix XI).

Therefore,

$$CQ^2 = \frac{S_w}{S} \times BQ \tag{37.7}$$

$$CQ^2 = 0.025 \times 1.87 = 0.05 \text{ m}$$

Total loss ($BQ + CQ^2$): It is the sum of aquifer loss and well loss, which is expressed in metre (m).

$$\text{Total loss} = 1.87 + 0.05 = 1.92 \text{ m}$$

Therefore, the pump should be designed for a loss of 1.92 m.

PROBLEM 38 Determine the (a) well loss, (b) formation loss and (c) total loss using the step-drawdown data given in Table 38.10. The non-pumping water level is 6.25 m.

Key Concept A step-drawdown test is a single-well pumping test which is designed to study the performance of a pumping well under controlled variable discharge conditions. In a step-drawdown test, the discharge rate in the pumping well increases from its low constant rate to higher constant rates through a sequence of pumping intervals (steps) of three to five. Each step is typically of equal duration, lasting from approximately 30 min to 180 min. Each step should be of sufficient duration to allow dissipation of wellbore storage effects. The test gives information on the conditions of the total well losses (well loss and formation loss).

Data of the given problem

Non-pumping water level = 6.25 m

Time since pumping started = 1.5 min to 100 min (Table 38.1)

Drawdown = 6.377 m to 8.500 m (Table 38.1)

Discharge = 0.0075 m^3/s to 0.0288 m^3/s (Table 38.1)

TABLE 38.1 Time-step Drawdown Data

Time since pumping started (min)		*Drawdown* (m)	*Discharge* (m^3/s)
Step I	1.5	6.377	0.0075
	2	6.381	
	3	6.390	
	4	6.399	
	5	6.429	
	6	6.468	
	7	6.489	
	8	6.500	
Step II	9	7.441	0.0210
	10	7.476	
	15	7.489	
	20	7.498	
	30	7.500	
	40	7.513	
Step III	50	8.308	0.0288
	60	8.319	
	70	8.440	
	90	8.449	
	100	8.500	

Solution

Time (*t*, min) since pumping started is plotted on *x*-axis and drawdown (*s*, m) is plotted on *y*-axis in a semi-logarithmic graph (Figure 38.1). The straight line is drawn passing through all the plotted points in each step. Increment drawdown is determined in each step for a pumping period of 60 min.

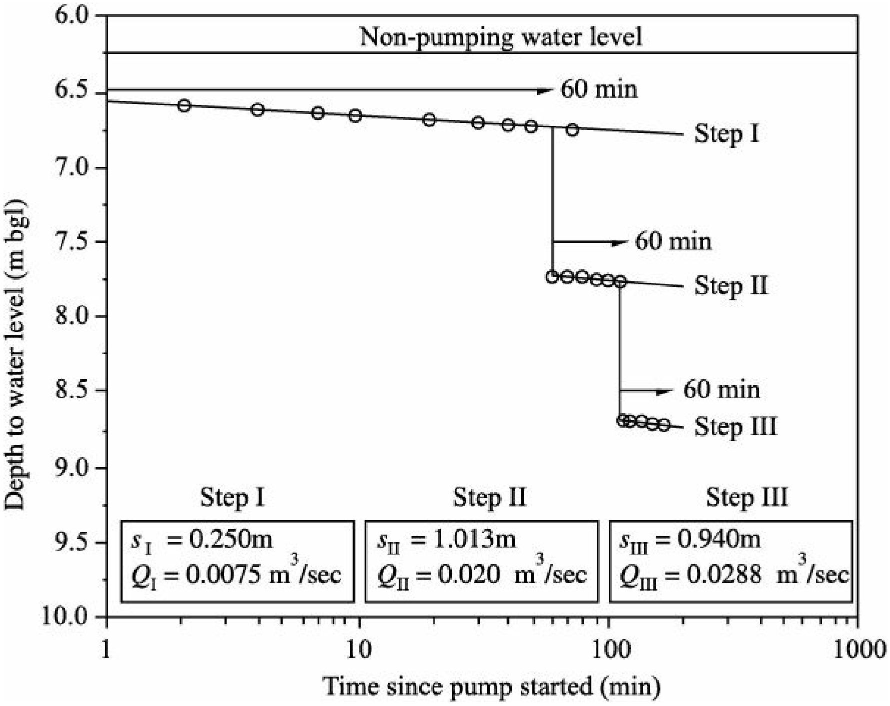


FIGURE 38.1 Time-drawdown data from step-drawdown pumping test.

The well loss, formation loss and the total loss can be calculated using Walton's method as well as Jacob's method. First, we have shown these calculations as per *Walton's method* (1962).

$$\text{(a) Well loss coefficient } (C) \text{ for step I and II} = \frac{\left(\frac{\Delta s_{II}}{\Delta Q_{II}}\right) - \left(\frac{\Delta s_I}{\Delta Q_I}\right)}{\Delta Q_I + \Delta Q_{II}} \tag{38.1}$$

$$\text{Well loss coefficient } (C) \text{ for step II and III} = \frac{\left(\frac{\Delta s_{III}}{\Delta Q_{III}}\right) - \left(\frac{\Delta s_{II}}{\Delta Q_{II}}\right)}{\Delta Q_{II} + \Delta Q_{III}} \tag{38.2}$$

where,

Δs = increment of drawdown (m) produced by each increase in the rate of pumping (Figure 38.1)

ΔQ = increase in the rate of pumping [(Figure 38.1); $Q_{II} - Q_I$ and $Q_{III} - Q_{II}$

Therefore, $$C \text{ for steps I and II} = \frac{\left(\frac{1.013}{0.0135}\right) - \left(\frac{0.250}{0.0075}\right)}{0.0075 + 0.0135} = 1{,}985.90 \text{ s}^2/\text{m}^5$$

Therefore, $$C \text{ for steps II and III} = \frac{\left(\frac{0.940}{0.0078}\right) - \left(\frac{1.013}{0.0135}\right)}{0.0135 + 0.0078} = 2{,}135.02 \text{ s}^2/\text{m}^5$$

$$\text{Average, } C = \frac{1{,}985.90 + 2{,}135.02}{2} = 2{,}060.46 \text{ s}^2/\text{m}^5$$

Therefore, the well loss (CQ^2) for maximum pumping rate (Q_{III}) of 0.0288 m^3/s is the product of well loss coefficient (C) and maximum pumping rate [Q_{III}; Eq. (38.3)], which is expressed in metre (m).

$$CQ^2 = C \times Q_{\text{III}} \tag{38.3}$$

Therefore, $$CQ^2 = 2{,}060.46 \times 0.0288^2 = 1.71 \text{ m}$$

(b) $$\text{Formation loss } (BQ) = \text{Total drawdown} - \text{Well loss} \tag{38.4}$$

$$\begin{aligned}\text{where, total drawdown} &= s_{\text{I}} + s_{\text{II}} + s_{\text{III}} \\ &= 0.250 + 1.013 + 0.940 = 2.203 \text{ m}\end{aligned}$$

Therefore, $$BQ = 2.203 - 1.71 = 0.493 \text{ m}$$

$$\text{Formation loss coefficient } (B) = \frac{BQ}{Q_{\text{III}}} \tag{38.5}$$

$$B = \frac{0.493}{0.0288} = 17.12 \text{ s/m}^2$$

(c) $$\text{Total loss} = \text{Well loss} + \text{Formation loss} \tag{38.6}$$

Therefore, $$\text{total loss} = 1.71 + 0.493 = 2.203 \text{ m}$$

$$\text{Total loss (\%)} = \left(\frac{\text{Well loss}}{\text{Total drawdown}} \times 100\right) + \left(\frac{\text{Formation loss}}{\text{Total drawdown}} \times 100\right) \tag{38.7}$$

Therefore, $$\begin{aligned}\text{total loss (\%)} &= \left(\frac{1.71}{2.203} \times 100\right) + \left(\frac{0.493}{2.203} \times 100\right) \\ &= 77.62\% + 22.38\% = 100\%\end{aligned}$$

Therefore, total loss (%) = $\left(\frac{1.71}{2.203} \times 100\right) + \left(\frac{0.493}{2.203} \times 100\right)$

The well loss is high (78%) so that the well design could have been improved.

Now, well loss, formation loss and total drawndown are calculated using

Jacob’s method (1947).

Figure 38.2 shows the plots of pumping rate on x-axis and specific drawdown on y-axis in an arithmetic graph. The straight line is drawn passing through the points to compute the slope value of C. Then, this value is used to calculate the formation loss, well loss and total drawdown (Table 38.2).

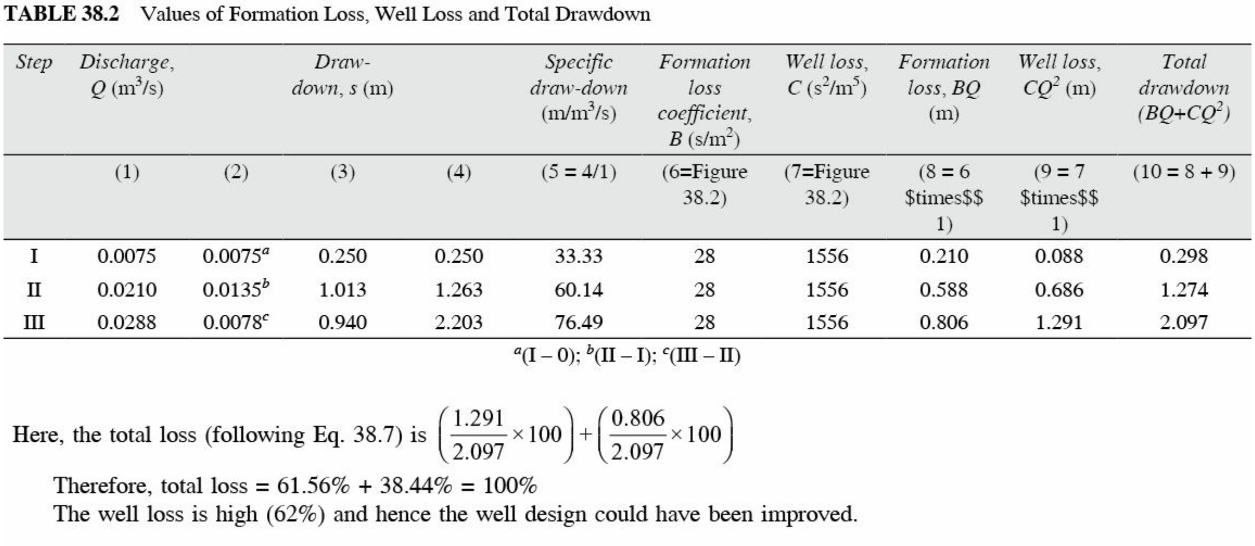


TABLE 38.2 Values of Formation Loss, Well Loss and Total Drawdown

Step	*Discharge*, Q (m^3/s)		*Draw-down*, s (m)		*Specific draw-down* (m/m^3/s)	*Formation loss coefficient*, B (s/m^2)	*Well loss*, C (s^2/m^5)	*Formation loss*, BQ (m)	*Well loss*, CQ^2 (m)	*Total drawdown* (BQ+CQ^2)
	(1)	(2)	(3)	(4)	(5 = 4/1)	(6=Figure 38.2)	(7=Figure 38.2)	(8 = 6 \$times\$\$ 1)	(9 = 7 \$times\$\$ 1)	(10 = 8 + 9)
I	0.0075	0.0075[a]	0.250	0.250	33.33	28	1556	0.210	0.088	0.298
II	0.0210	0.0135[b]	1.013	1.263	60.14	28	1556	0.588	0.686	1.274
III	0.0288	0.0078[c]	0.940	2.203	76.49	28	1556	0.806	1.291	2.097

[a](I – 0); [b](II – I); [c](III – II)

Here, the total loss (following Eq. 38.7) is $\left(\dfrac{1.291}{2.097}\times 100\right)+\left(\dfrac{0.806}{2.097}\times 100\right)$

Therefore, total loss = 61.56% + 38.44% = 100%

The well loss is high (62%) and hence the well design could have been improved.

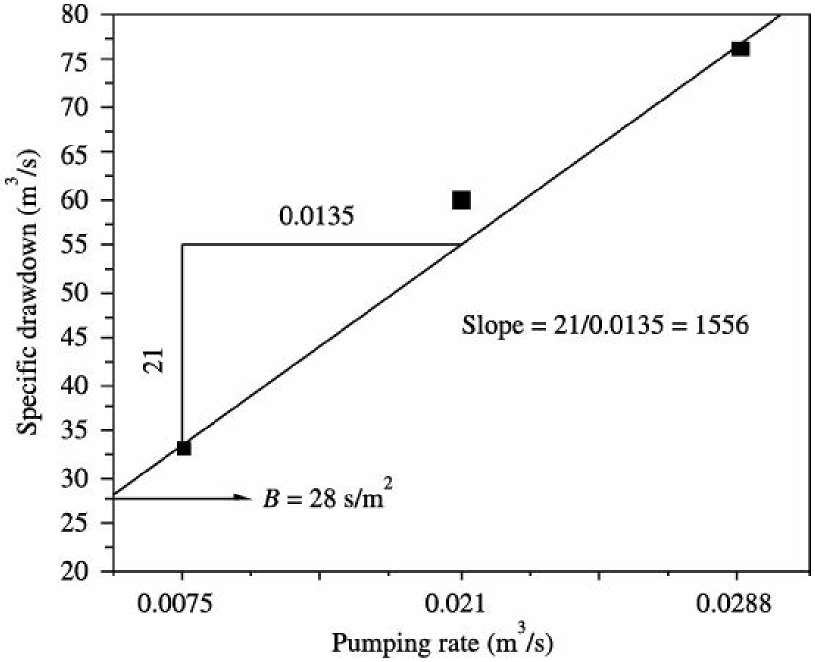


FIGURE 38.2 Plot of pumping rate versus specific drawdown of step-drawdown test.

PROBLEM 39 Determine the formation loss and well loss from the discharge drawdown data obtained from a production in a step-drawdown test (Table 39.1), using Rorabaugh’s method.

Key Concept Rorabaugh's method (1953) is one of the procedures for the estimation of formation loss and well loss from the data of the discharge, drawdown obtained from the step-drawdown test.

Data of the given problem

TABLE 39.1 Discharge Drawdown Data

Q (m^3/day)	250	500	1,000	2,000
S_w (m)	0.798	1.795	4.700	16.600

Solution

Specific drawdown: It is the ratio of the resulting drawdown to the well discharge [Eq. (39.1)], which is expressed in metre (m). The calculated values are shown in Table 39.2.

$$\text{Specific drawdown} = \frac{S_w}{Q} \tag{39.1}$$

where,

S_w = resulting drawdown (m)

Q = discharge (m^3/day)

TABLE 39.2 Computation of Specific Drawdown

Q (m^3/day)	250	500	1,000	2,000
S_w	0.798	1.795	4.700	16.600
$\frac{S_w}{Q}$	0.00319	0.00359	0.0047	0.0083

Here,

$$S_w = BQ + CQ^n \tag{39.2}$$

$$\frac{S_w}{Q} = B + CQ^{n-1} \tag{39.3}$$

$$\frac{S_w}{Q} - B = CQ^{n-1} \tag{39.4}$$

$$\log\left[\left(\frac{S_w}{Q}\right) - B\right] = \log C + (n-1)\log Q \tag{39.5}$$

where,

Q = discharge (m^3/day)
S_w = resulting drawdown (m)
$\frac{S_w}{Q}$ = specific drawdown
BQ = formation loss (m)
CQ = well loss (m)
B = coefficient of formation loss (s/m^2)
C = coefficient of well loss (s^2/m^5)

Equation (39.5) shows that a plot of $\left(\frac{S_w}{Q}\right) - B$ against Q on double logarithmic graph should have a straight line, whose slope is $m = n - 1$, and when $Q = 1$, $C = \left(\frac{S_w}{Q}\right) - B$. Therefore, the values of B are tried, till a straight line plot is obtained (Figure 39.1). Here, the value of B is 0.003 day/m^2 (Table 39.3), which shows a straight line. The resulting straight line ($n - 1$) is 1.7 so that n is 2.7. C is computed from Eq. (39.6), using arbitrary combinations of Q and S_w.

$$S_w = BQ + CQ^{2.7} \tag{39.6}$$

TABLE 39.3 Computation of $\left(\frac{S_w}{Q}\right) - B$ Values

B (day/m^2)	Q (m^3/day)			
	250	500	1,000	2,000
0	0.00319	0.00359	0.00470	0.00830
0.001	0.00219	0.00259	0.00370	0.00730

0.002	0.00119	0.00159	0.00270	0.00630
0.003	0.00019	0.00059	0.00170	0.00530
0.004	–	–	0.00070	0.00430

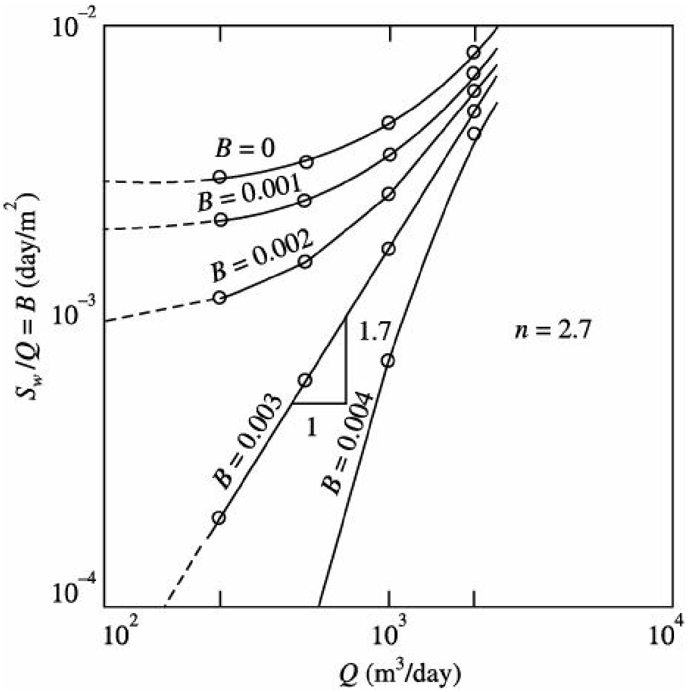


FIGURE 39.1 Graphical method for determination of well losses.

If Q and S_w are 2,000 m^3/day and 16.60 m, respectively, C is computed as 6×10^{-8} day $^{2.5}$/m$^{6.5}$. Using the values of B, C and n, the formation losses and well losses for the different Q values are shown in Table 39.4.

TABLE 39.4 *BQ* and *CQ* for Different *Q* Values

Q (m^3/day)	250	500	1,000	2,000
BQ (m)	0.75	1.50	3.00	6.00
CQ^2 (m)	0.05	0.30	1.70	10.60
S_w	0.80	1.80	4.70	16.60
BQ (%) in total losses	93.75	83.33	63.83	36.14
CQ^2 (%) in total losses	6.25	16.67	36.17	63.86

***Note*:**

a. $S_w = BQ + CQ^2$;
b. $BQ = 0.003 \times 250$; 0.003×500; $0.003 \times 1{,}000$ and $0.003 \times 2{,}000$
c. $CQ^2 = 0.00019 \times 250$; 0.00059×500; $0.00170 \times 1{,}000$ and 0.00530

$\times$ 2,000

d. BQ (%) = $\frac{S_w - CQ^2}{S_w} \times 100$

e. CQ^2 (%) = $\frac{S_w - BQ}{S_w} \times 100$

Since the well losses for discharge of 2,000 m^3/day exceeds 64% of the total losses, it indicates improper design and development of the well or deterioration of the screen.

PROBLEM 40 The result of a mechanical analysis of the soil sample observed from a well and the litho-log of the well are the shown in data. The screen of the well is to be placed between 35 m and 45 m. If the thickness of the aquifer material is 10 m, the expected yield from the well is 850 lpm and the recommended well diameter is 20 cm, determine the well components for the selection of the natural gravel-packed or artificial gravel-packed well.

Key Concept An optimum well design requires a screen that is surrounded by a material having coarses grain size than the natural aquifer. Thus, higher velocities can be obtained adjacent to the screen without excessive head loss or outflow of the fine material. Screened wells in the unconsolidated formations can be divided as (a) natural gravel-packed wells and (b) artificial gravel-packed wells (Figure 40.1), depending on the methods of construction, development and hydraulic performance.

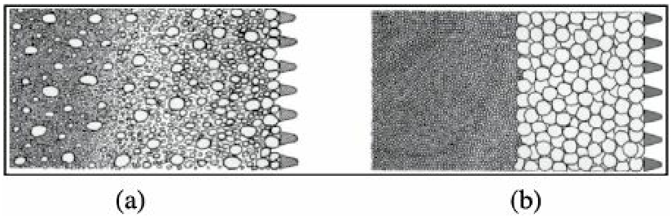

(a) (b)

FIGURE 40.1 (a) Natural gravel-pack and (b) artificial gravel pack.

In the natural gravel-packed well, the screen is placed directly in contact with the aquifer [Figure 40.1(a)]. Thus, the finer material from the aquifer close to the screen should be removed by the coarse material, thereby increasing the porosity and hydraulic conductivity of the formation in the vicinity of the well.

In artificial gravel-packed well, a gravel of suitable size is placed around the screen to improve the discharging capacity of the well [Figure 40.1(b)]. The replacement of the finer material around the screen by gravel pack of coarser and uniform size material stabilises the fine-grained and poor sand aquifers, which permits the use of larger slot opening, resulting in better efficiency of the well in fine-grained aquifers, and increases the effective radius of the well. In the case of several aquifers of different sizes, it permits the use of single slot size.

Data of the given problem

Figure 40.2 shows the result of a mechanical analysis of the soil sample observed from a well and Table 40.1 shows the litho-log of the well.

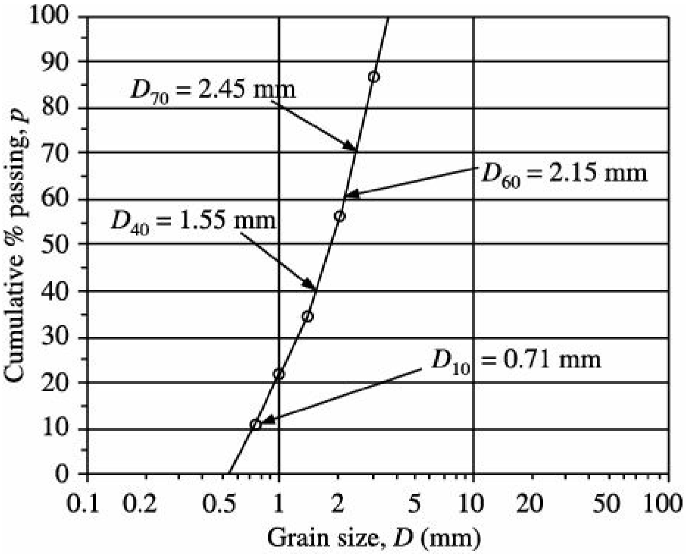


FIGURE 40.2 Grading curve.

TABLE 40.1 Particulars of Litho-log

Depth (m)	*Strata*
0 to 29	Clay
29 to 35	Fine sand
35 to 45	Coarse sand
> 45	Clay

$$\text{Expected yield} = 850 \text{ lpm or } \frac{850 \times 1{,}000}{60} \text{ m}^3/\text{s}$$

$$\text{Thickness of the aquifer} = 10 \text{ m}$$

$$\text{Recommended well diameter} = 20 \text{ cm or } 0.20 \text{ m}$$

$$\text{Effective grain size } (D_{10}) = 0.71 \text{ mm}$$

$$\text{Grain size } (D_{40}) = 1.55 \text{ mm}$$

$$\text{Screen grain size } (D_{60}) = 2.15 \text{ mm}$$

$$\text{Grain size } (D_{70}) = 2.45 \text{ mm}$$

$$\text{Uniformity coefficient } (C_u) = \frac{D_{60}}{D_{10}} \tag{40.1}$$

$$C_u = \frac{2.15}{0.71} = 3.03$$

Solution

In case of confined conditions

(a) Length of the screen (L_s): It is three-fourth of the aquifer thickness, which is the desirable length of the screen for homogenous aquifer material in case of confined aquifer [Eq. (40.2)]. It is expressed in metre (m).

$$L_s = \frac{3}{4} \times b \tag{40.2}$$

where,

b = thickness of the aquifer material (m)

Therefore, $L_s = \frac{3}{4} \times 10 = 7.5$ m

(b**)** *Screen entrance velocity (V_e):* It is the ratio of well discharge to screen open area, screen diameter and screen length (Eq. 40.3), which is expressed in centimetre per second (cm/s).

$$V_e = \frac{Q}{A_p \pi D_s L_s} \tag{40.3}$$

where,

V_e = screen entrance velocity (cm/s)

Q = discharge (m^3/s)

A_p = open area of the screen (>15% of the total surface area of the screen)

D_s = diameter of the screen (cm) with respect to yield
L_s = length of the screen (m)

Therefore,
$$V_e = \frac{\dfrac{850 \times 1{,}000}{60}}{0.15 \times 3.14 \times 20 \times 7.5 \times 100} = 2.01 \text{ cm/s}$$

a. To ensure a long-term service of the well, movement of the finer fractions of the aquifer material, resulting in subsequent clogging of the screen openings, has to be minimised.
b. The aquifers of low hydraulic conductivity are generally composed of fine grained material compared to aquifers of high hydraulic conductivity. Thus, the possibility of clogging depends on the grain size of the fine aquifer material, which, in turn, depends on its hydraulic conductivity.
c. The ideal entrance velocity should be less than 3 cm/s.
d. In the present case, the entrance velocity (2.01 cm/s) is less than the ideal one (3 cm/s). Thus, this is acceptable.

Conditions for the design of natural gravel-packed well are as follows:

a. The effective grain size (D_{10}) should be more than 0.25 mm.
b. The uniformity coefficient (C_u) should be higher than 2.5.
c. In the present case, the values of D_{10} (0.71 mm) and C_u (3.03) are more than that of the recommended values for the design of natural gravel-packed well.

Slot size of the screen: It is determined as follows:

a. The size of the openings is determined by the screen grain size (D_{60}) of the aquifer material, as a slot size is to allow formation material to be retained outside the well and the rest (60%) to move into the well to be washed out by a compressor or pump.
b. The selective removal of fines from aquifer material in contact with and surrounding the slotted or screened sections creates a natural strain and enhances the hydraulic conductivity around the well.

c. In practice, the openings are to be selected on the basis of 30% to 60% retention
(D_{70} to D_{40}). Therefore, the ideal screen slot size is 2.45 mm to 1.55 mm (D_{70} to D_{40}) or 2 mm (on average).

In case of unconfined conditions

(a) *Length of the screen (L_s):* It is one-third of the aquifer thickness, which is the desirable length of the screen for homogenous aquifer material in case of unconfined condition [Eq. (40.4)], It is expressed in metre (m).

$$L_s = \frac{1}{3} \times b \tag{40.4}$$

where,

b = thickness of the aquifer material (m)

Therefore, $$L_s = \frac{1}{4} \times 10 = 3.03 \text{ m}$$

(b) *Screen entrance velocity (V_e)*: It is the ratio of well discharge to screen open area, screen diameter and screen length [Eq. (40.5)], which is expressed in centimetre per second (cm/s).

$$V_e = \frac{Q}{A_p \pi D_s L_s} \tag{40.5}$$

where,

V_e = screen entrance velocity (cm/s)

Q = discharge (m^3/s)

A_p = open area of the screen (>15% of the total surface area of the screen)

D_s = diameter of the screen (cm) with respect to yield

L_s = length of the screen (m)

Therefore, $$V_e = \frac{\dfrac{850 \times 1{,}000}{60}}{0.15 \times 3.14 \times 20 \times 3.03 \times 100} = 4.96 \text{ cm/s}$$

Here, the entrance velocity (4.96 cm/s) is higher than that of the recommended one (3 cm/s) so that it is reduced to less than 3 cm/s. Thus, the length of the screen is selected to be 4.5 m instead of the computed one (3.03

m) and the open area of the screen is to be increased to 18% instead of 15% to reduce the entrance velocity.

Then,
$$V_e = \frac{\dfrac{850 \times 1{,}000}{60}}{0.18 \times 3.14 \times 20 \times 4.5 \times 100} = 2.78 \text{ cm/s}$$

Slot size of the screen: The selected slot size of the screen is 2 mm as in the case of confined condition.

PROBLEM 41 Grading curve of the mechanical analysis of the soil sample is presented in Figure 41.1. The thickness of the aquifer material is 10 m and the well efficiency is 60%. Determine the type of well for the design of natural gravel pack or artificial gravel pack.

Key Concept From the grain size analysis and well efficiency, it can be possible to select the well design with respect to natural gravel-packed well or artificial gravel-packed well, depending on the nature of aquifer material present in the sub-surface, and also, to estimate the probable drawdown in the well.

Data of the given problem

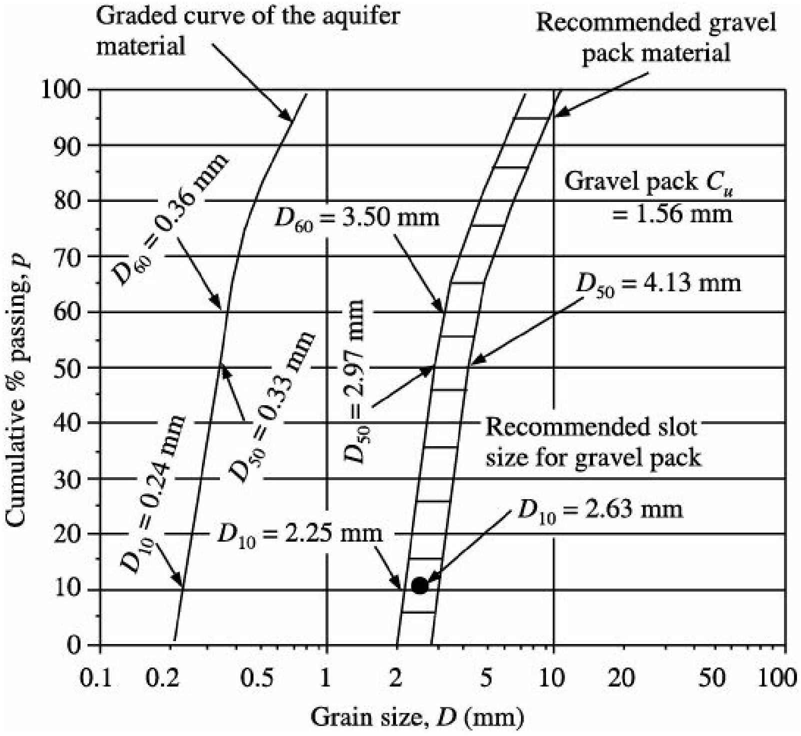


FIGURE 41.1 Grading curve.

Thickness of the aquifer material = 10 m
Well efficiency = 60%

TABLE 41.1 Results of Grading Curve (Figure 41.1)

Grain size	*Aquifer material*	*Artificial gravel-pack*
Effective grain size D_{10}	0.24 mm	2.25 mm
Median grain size D_{50}	0.33 mm	2.97 mm
Screen grain size D_{60}	0.36 mm	3.50 mm
Uniformity coefficient (C_u)	1.50	1.56

Solution

For design of natural gravel-packed well

a. The effective grain size (D_{10}) should be more than 0.25 mm.
b. The uniformity coefficient (C_u) should be higher than 2.5.
c. In the present case (Table 41.1), the values of D_{10} (0.24 mm) and C_u (1.50) are less than that of the recommended values for the design of natural gravel-packed well.

For design of artificial gravel-packed well

a. The effective grain size (D_{10}) should be less than 0.25 mm.
b. The uniformity coefficient (C_u) should be less than 3 for the homogenous material.
c. If the uniform aquifer (C_u) is less than 2, the ratio of gravel pack to aquifer $\left(\frac{D_{50}\text{ of gravel pack}}{D_{50}\text{ of acquire}}\right)$ should be between 9 and 12.5; if it is more than 2, the latter should be between 12 and 15.5.

Present case

a. Here, D_{10} is less than 0.25 mm (0.24 mm), C_u is less than 2 (1.50) and the median grain size D_{50} is 0.33 mm. Thus, the ratio of gravel pack to aquifer varies from 2.97 (0.33 × 9) mm to 4.13 (0.33 × 12.5) mm.

b. The lines are drawn through these two points (2.97 mm and 4.13 mm; Figure 41.1) so that each gives a C_u of less than 2 (1.56).

c. The slot size of the screen should be equal to the effective grain size D_{10} of the gravel-pack material so that the recommended slot size is 2.63 mm.

d. The recommended size of the gravel is 3 mm to 10 mm. The gravel pack thickness is 15 to 20 cm.

Estimation of probable drawdown

Hydraulic conductivity **(*K*)** *(Allen Hazen's formula, 1905):* It is the product of constant and effective grain size [Eq. (41.1)], which is expressed in metre per day (m/day) or centimetre per second (cm/s).

$$K = CD_{10}^2 \tag{41.1}$$

where,

C = constant (850, Table 17.1)

D_{10} = effective grain size (mm)

Therefore, $K = 850 \times (0.024)^2 = 0.4896$ cm/s

The computed K appears to be in higher side so that it should be reduced to $\frac{2}{4}$.

Then, $K = \frac{2}{4} \times 0.4896 = 0.2448$ cm/s or 0.002448 mm/s

Transmissivity (T): It is the product of the hydraulic conductivity and aquifer thickness [Eq. (41.2)], which is expressed in square metre per day (m^2/day).

$$T = Kb \tag{41.2}$$

where,

K = hydraulic conductivity (m/day)

b = thickness of the aquifer (m)

Therefore, $T = 0.002448 \times 10 = 0.02448$ m^3/s/m

Specific capacity (C): It is the product of transmissivity and well efficiency

[Eq. (41.3)], which is expressed in cubic metre per second per metre ($m^3/s/m$).

$$C = \frac{T}{1.4} \times \text{Well efficiency} \qquad (41.3)$$

where,

T = transmissivity (m^2/day)

Therefore, $$C = \frac{0.02448}{1.4} \times \frac{60}{100} = 0.0105 \text{ m}^3\text{/s/m}$$

Probable drawdown (S_w): It is the ratio of aquifer thickness to transmissivity [Eq. (41.4)], which is expressed in metre (m).

$$S_w = \frac{b}{T} \qquad (41.4)$$

where,

b = thickness of the aquifer (m)

T = transmissivity (m/day)

Therefore, $$S_w = \frac{1}{60 \times 0.0105} = 1.59 \text{ m}$$

Therefore, the computed drawdown is permissible.

PROBLEM 42 Litho-log data of a deep well is shown in Figure 42.1. The depth of the drilled well is 75 m. The diameter of the well is 30 cm. The static water level is 16 m. The discharge of the well is 2,000 lpm with a drawdown of 5 m. The hydraulic conductivity of the sandy aquifer material is 25 m/day. The radius of the influence is 250 m.

a. Determine the (i) length of the screen (strainer) required and (ii) its place in depth.
b. For lifting of water to a height of 25 m agl, estimate the power of pump required. Assume the total loss is 6 m and the pump efficiency is 60%.
c. Calculate the monthly electric bill for running the pump for 9 hours, if the rate of unit of electricity power (kW) is ` 1.50 and the motor efficiency is 80%.

Note:

a. Screen entrance velocity is 25 mm/s.

b. Open area for the screen is 15%.
c. Clogging coefficient is 0.5 (50% of the open area is clogged).

> ***Key Concept*** For the selection of the well screen to be placed in a well, it is necessary to compute the length of the screen, drawdown conditions and well yields of the well. According to the well yield and pump efficiency, it can be possible to estimate the power of pump and monthly electrical bill.

Data of the given problem

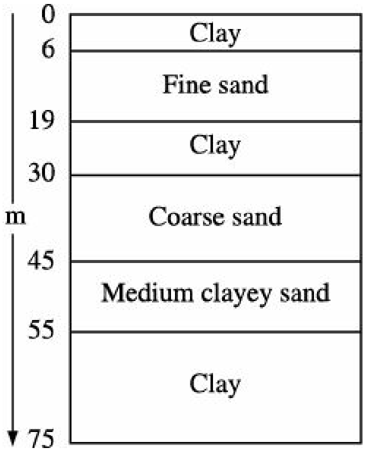


FIGURE 42.1 Litho-log data of deep well.

Diameter of the drilled well = 30 cm or 0.3 m

Static water level = 16 m

Discharge = 2,000 lpm or 2 cm/h $\left(\frac{2,000}{1,000 \times 60}\right)$

Drawdown = 5 m

Hydraulic conductivity = 25 m/day or $\frac{25}{60 \times 60 \times 24}$ m/s

Radius of the influence = 250 m

Height of water lifted = 25 m

Total loss = 6 m

Pump efficiency = 60%

Running of pump per day = 9 hours

Rate of unit of kW = ` 1.50

Motor efficiency = 80% or 0.80
Screen entrance velocity = 25 mm/s or 0.025 cm/s
Open area for the screen = 15% or 15
Clogging coefficient = 0.5

Solution

(a) (i) Length of the screen (L_s): It is the ratio of well discharge to the product of coefficient of clogging, well diameter, well open area and screen entrance velocity [Eq. (42.1)], which is expressed in metre (m).

$$L_s = \frac{Q}{C_c \pi D_d A_p V_e} \tag{42.1}$$

where,
Q = well discharge (m^3/day)
C_c = coefficient of clogging
D_d = diameter of the well (cm)
A_p = open area of the screen (%)
V_e = entrance velocity of the screen (cm/s)

Therefore,

$$L_s = \frac{\frac{2,000}{1,000 \times 60}}{0.5 \times 3.14 \times 0.3 \times 0.15 \times 0.025} = 18.87 \text{ m}$$

(a)(ii) Location of the length of screen: It is the ratio of the hydraulic conductivity, well screen and drawdown to the influence of radius and well radius [Eq. (42.2)], which is expressed in metre (m).

$$Q = \frac{2.72 K L_s S_w}{\log \frac{r_o}{r_w}} \tag{42.2}$$

Then,

$$S_w \text{ (drawdown)} = \frac{Q \log \frac{r_o}{r_w}}{2.72 K L_s} \tag{42.3}$$

where,
Q = discharge (lpm)
K = hydraulic conductivity (m/day or m/s)
L_s = length of the screen (m)
S_w = drawdown (m)

r_o = influence of radius (m)

r_w = radius of the well (m)

Therefore, $$S_w = \frac{\dfrac{2,000}{1,000 \times 60} \log \dfrac{250}{0.15}}{2.72 \times \dfrac{25}{86,400} \times 18.87} = 7.22 \text{ m}$$

Here, the calculated drawdown (S_w) is higher (7.22 m) than that of the observed one (5 m) due to partial screening. Thus, the calculated drawdown should be limited to 5 m. Then, the pumping rate (Q) of well is

$$Q = \frac{2,000 \times 5}{7.22} = 1,385.04 \text{ or } 1,385 \text{ lpm}$$

Therefore, the screen of the well is to be placed in the coarse sand strata (30 m to 45 m depth from the ground level).

(b) Power of pump required (*p*): It is the ratio of water density, well discharge and total head to the pump efficiency [Eq. (42.4)], which is expressed in kilowatts (kW).

$$p = \frac{\rho g Q H}{1,000 n_o} \tag{42.4}$$

where,

ρ = density of the water (1,000 kg/m^3)

g = acceleration due to gravity (9.81 m/s^2)

Q = well discharge (m/day)

H = total head [drawdown (S_w) + static water level (SWL)

+ height of the water lifted (h) + total loss (t_l) = 7.22 + 16 + 25 + 6 = 54.22 m]

n_o = pump efficiency (%)

Therefore, $$p = \frac{1,000 \times 9.81 \times \dfrac{2}{60} \times 54.22}{1,000 \times 0.60} = 29.52 \text{ or } 30 \text{ kW}$$

(c) Monthly electricity bill (*mel*): It is the product of the power of motor, height of water lifted, running of pump and rate of unit [Eq. (42.5)], which is expressed as rupees (`).

$$mel = p_m \times h \times r_p \times r_{kW} \qquad (42.5)$$

where,

p_m = power of the motor

h = height of the water lifted

r_p = running of the pump per day

r_{kW} = rate of the unit per kW

Power of motor (pm): It is the ratio of the power of pump required to the motor efficiency [Eq. (42.6)], which is expressed in kilowatt (kW).

$$pm = \frac{p}{n_m} \qquad (42.6)$$

where,

p = power of the pump required (kW)

n_m = motor efficiency

$$pm = \frac{30}{0.80} = 37.50 \text{ kW}$$

Therefore, $mel = 37.50 \times 25 \times 9 \times 1.50 =$ ₹ 12,656.25

7

Groundwater Management

PROBLEM 43 In an area of 5 km^2, the annual rainfall, annual water level fluctuation, specific yield and population are 950 mm, 3 m, 3% and 250 per km^2, respectively. The rate of infiltration of the area is 10% and the consumption of water per head per day is 140 l. Estimate the (a) availability of groundwater storage, (b) replenishable groundwater, (c) water requirement of the local people, and (d) average availability of groundwater compared to the water requirement for drinking.

Key Concept Potentiality of the groundwater resource can be estimated using two simple methods—(a) a product of the area, water level fluctuation and specific yield, and (b) a product of the area, annual rainfall and rate of infiltration. The average of these two methods depicts the overall availability of groundwater quantity. Accordingly, it can be possible to use the water properly without any overdraft.

Data of the given problem

Area = 5 km^2 or 5 × 10^6 m

Annual rainfall = 950 mm or 0.950 cm

Annual water level fluctuation = 3 m or 0.03 cm

Specific yield = 3% or 0.3

Population = 250 per km^2

Rate of infiltration = 10% or 0.1

Consumption of water per head per day = 140 l

Solution

(a) Availability of groundwater storage (A_g): It is the product of the area, water level fluctuation and specific yield [Eq. (43.1)], which is expressed in cubic metre (m^3).

$$A_g = \text{Area} \times \text{Water level fluctuation} \times \text{Specific yield} \tag{43.1}$$

Therefore,
$$A_g = 5 \times 10^6 \times 3 \times \frac{3}{100} = 4{,}50{,}000 \text{ m}^3$$

(b) Replenishable groundwater (R_g): It is the product of the area, annual rainfall and rate of infiltration of soil [Eq. (43.2)], which is expressed in cubic metre (m^3).

$$R_g = \text{Area} \times \text{Annual rainfall} \times \text{Rate of infiltration} \tag{43.2}$$

Therefore,
$$R_g = 5 \times 10^6 \times \frac{950}{1{,}000} \times \frac{10}{100} = 4{,}75{,}000 \text{ m}^3$$

(c) Water requirement (W_r): It is the product of the population, water consumption and time [in 365 days; Eq. (43.3)], which is expressed in cubic metre (m^3).

$$W_r = \text{Population} \times \text{Water consumption} \times \text{Time} \tag{43.3}$$

Therefore,
$$W_r = 250 \times 140 \times 365 = 12{,}775{,}000 \text{ l or } 12{,}775 \text{ m}^3$$

(d) Average availability of groundwater compared to the requirement: It is the calculated as shown below:

Average availability of groundwater (AA_g): It is the amount of average availability of groundwater storage and replenishable groundwater [Eq. (43.4)], which is expressed in cubic metre (m^3).

$$AA_g = \frac{A_g + R_g}{2} \tag{43.4}$$

where,

A_g = availability of groundwater storage (m^3)
R_g = replenishable groundwater (m^3)

Therefore,
$$AA_g = \frac{4{,}50{,}000 + 75{,}000}{2} = 4{,}62{,}500 \text{ m}^3$$

Availability of groundwater compared to the requirement (AGR): It is the ratio of the average availability of groundwater to the water requirement [Eq. (43.5)].

$$AGR = \frac{AA_g}{W_r} \tag{43.5}$$

where,

AA_g = Average availability of groundwater (m^3)

W_r = Water requirement (m^3)

Therefore, $$AGR = \frac{4,62,500}{12,775} = 36.20$$

Thus, there is a lot of groundwater (about 36 times more than the requirement) for drinking in the area so that no question of overdraft in the area.

PROBLEM 44 In an area of 30 km^2, the received annual rainfall is 750 mm. The area comprises 60% of the hilly terrain and the rest 40% plain land. The rate of infiltration of the rainfall is 3% in the hilly terrain and 9% in the plain land. The required annual water supply is 1.45 million cubic metre (Mm^3) for a proposed satellite township. Estimate the water supply condition, whether it is sufficient or deficient to meet the required annual water supply for the proposed township.

Key Concept In the hilly terrain, the potentiality of the groundwater resource is not uniform, even though the rainfall is the same in the entire area. Generally, the ground surface at higher topography in the hard rock terrain has low porosity and permeability characteristics compared to the plain land, which shows higher porosity and permeability characteristics due to the development of secondary porosity and depositional environment. And, the slope of the hilly terrain is higher relative to the plain land, which supports a higher runoff in the former area. Thus, the rate of infiltration is more in the plain land than that in the hilly terrain. Therefore, the rate of infiltration of the ground is the detrimental factor for the assessment of the potentiality of the groundwater resources in the hilly terrain as well as in the plain land under the same rainfall condition.

Data of the given problem

Area = 30 km^2 or 30×10^6 m

Area of the hilly terrain = 60% (18 km^2 or 18×10^6) of the area

Area of the plain land = 40% (12 km^2 or 12×10^6 m) of the area

Annual rainfall = 750 mm or 0.750 cm

Rate of infiltration = 3% (0.3) in the hilly terrain and 9% (0.9) in the plain land

Required water supply = 1.45 Mm^3 or 1,450,000 l

Solution

Estimated water supply: It is the product of the area, annual rainfall and rate of infiltration [Eq. (44.1)], which is expressed in cubic metre (m^3).

$$\text{Estimated water supply} = \text{Area} \times \text{Annual rainfall} \times \text{Rate of infiltration} \tag{44.1}$$

In hilly terrain,

$$\text{The estimated water supply } (H_r) = 18 \times 10^6 \times \frac{750}{1{,}000} \times \frac{3}{100}$$

Therefore, $$H_r = 405{,}000 \text{ m}^3 \quad \text{or} \quad 0.405 \text{ Mm}^3$$

In plain land,

$$\text{The estimated water supply } (P_l) = 12 \times 10^6 \times \frac{750}{1{,}000} \times \frac{9}{100}$$

Therefore, $$P_l = 810{,}000 \text{ m}^3 \quad \text{or} \quad 0.810 \text{ Mm}^3$$

Total water supply (T_w): It is the total amount of estimated water supply in the hilly terrain and plain land [Eq. (44.2)], which is expressed in cubic metre (m^3).

$$T_w = H_r + P_l \tag{44.2}$$

Therefore, $$T_w = 0.405 + 0.810 = 1.22 \text{ Mm}^3$$

$$\text{Required water supply } (R_s) = 1.45 \text{ Mm}^3$$

Water supply condition (*WSC*): It is the difference amount between the required water supply and total water supply [Eq. (44.3)], which is expressed in cubic metre (m^3).

$$WSC = R_s - T_w \tag{44.3}$$

Therefore, $$WSC = 1.45 - 1.22 = 0.23 \text{ Mm}^3$$

Thus, there is a water deficit of 0.23 Mm^3 in the proposed township.

PROBLEM 45 In an area of 900 km^2, the average water level fluctuation, the average storage coefficient, the average well yield and the annual pumping days are 10 m, 0.0006, 25 m^3/hour and 200, respectively. Estimate the (a) annual groundwater storage and (b) number of wells to be drilled in the area.

Key Concept Estimation of a number of wells to be drilled in an area depends on the availability of the groundwater resources. The potentiality of the groundwater resource can be computed on the basis of the area, water level fluctuation and storage coefficient of the aquifer material. However, the recommendation of a number of drilling sites should not be leading to wells interference and overdraft conditions.

Data of the given problem

Area = 900 km^2 or 900 × 10^6 m
Average water level fluctuation = 10 m
Average storage coefficient = 0.0006
Average well yield = 25 m^3/hour or 25 × 24 m^3/day
Annual pumping days = 200

Solution

(a) Annual groundwater storage: It is the product of the area, water level fluctuation and storage coefficient [Eq. (45.1)], which is expressed in cubic metre (m^3).

$$\text{Annual groundwater storage} = \text{Area} \times \text{Water level fluctuation} \times \text{Storage coefficient} \qquad (45.1)$$

$$\text{Therefore, groundwater storage} = 900 \times 10^6 \times 10 \times 0.0006 = 5{,}400{,}000 \text{ m}^3 \text{ or } 5.4 \text{ Mm}^3$$

(b) Number of wells to be drilled: It is the ratio of annual groundwater storage to annual draft [Eq. (45.2)].

$$\text{Number of wells to be drilled} = \frac{\text{Annual groundwater storage}}{\text{Annual draft}} \qquad (45.2)$$

Annual draft: It is the product of the well yield and annual pumping time [in days; Eq. (45.3)], which is expressed in cubic metre (m^3).

$$\text{Annual draft} = \text{Well yield} \times \text{Annual pumping days} \tag{45.3}$$

Therefore, $\text{annual draft} = 25 \times 24 \times 200 = 1{,}20{,}000 \text{ m}^3 \quad \text{or} \quad 0.12 \text{ Mm}^3$

Thus, number of wells to be drilled $= \dfrac{5.4}{0.12} = 45$ wells

PROBLEM 46 The average base flows measured from two parallel drains located 2,000 m apart are 3,000 m^3/day and 3,300 m^3/day at two upstream points *A* and *B* in an area under irrigation throughout the year. The base flows measured at 1,500 m downstream are 7,000 m^3/day and 7,400 m^3/day (see Figure 46.1). Compute the average rate of recharge.

Key Concept In any area, the rate of recharge is not uniform, as it varies with time. Thus, the utilisation of the average groundwater levels can give information about the rate of recharge, which is equivalent to an effective average rate of accretion, provided there is no artificial withdrawal from storage. The contribution to the base flow of the stream can be determined from the stream flow measurements. And the rate of recharge can be estimated using Jacob's formula, which is an equation for a steady-state water table profile.

Data of the given problem

Total base flow at points *A* and *B* = 6,300 (3,000 + 3,300) m^3/day

Total base flow at points *C* and *D* = 14,400 (7,000 + 7,400) m^3/day

Distance between the drains = 2,000 m

Increase of base flow over 2,000 m in the two drains = 8,100 m^3/day (14,400 – 6,300)

Average base flow per metre length of drain = $2.70 \text{ m}^3/\text{day} \left(\dfrac{8{,}100}{2 \times 1{,}500} \right)$

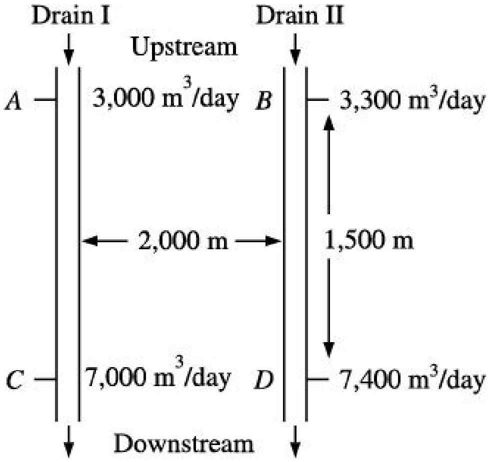


FIGURE 46.1 Layout of drains.

Solution

Average rate of recharge (*w*) [according to Jacob's formula (1943)]: It is the ratio of the average base flow per metre length of drain to the distance between the drains [Eq. (46.1)], which is expressed in centimetre per year (cm/year).

$$w = 5.256 \times 10^7 \frac{Q_b}{2a} \tag{46.1}$$

where,

Q_b = average base flow per metre length of drain (m^3/day)
$2a$ = distance between the two drains (m)

Therefore, $$w = 5.256 \times 10^7 \times \frac{2.70}{2{,}000 \times 1{,}440} = 49.28 \text{ cm/year}$$

PROBLEM 47 A jetting tool has four nozzles with 5 mm diameter at the end of a pipe having 4 cm diameter with a friction factor of 0.01. It requires working at a depth of 90 m. For obtaining an efflux velocity of 35 m/s, what capacity of the pump would be required?

Key Concept Well pumps produce flow by transforming mechanical energy to hydraulic energy. The selection of a particular size and type of pump depends on many factors, including pumping capacity, well diameter and its depth, variability and depth of pumping level, straightness of the well, sand pumping, total pumping head, pumping duration, type of power available and costs. Further, the size and number of nozzles depend on the capacity of the pump. The size of the pipe for feeding water to the nozzles should be large enough to keep the friction losses to reasonable value. Accordingly, the required capacity of the pump can be estimated.

Data of the given problem

Nozzle diameter = 5 mm or 0.005 m

Pipe diameter = 4 cm or 0.04 m

Friction factor = 0.01

Required depth = 90 m

Efflux velocity = 35 m/s

Solution

Calculating capacity of the pumps,

Discharge through four nozzles ($4V_a$): It is the product of diameter of pipe and nozzle [Eq. (47.1)], which is expressed in cubic metre per second (m^3/s).

$$4V_a = d_p V_a \frac{\pi}{4} d_n^2 \tag{47.1}$$

where,

V_a = velocity of the efflux (m/s)
d_p = diameter of the pipe (cm)
d_n = diameter of the nozzle (mm)

Therefore, $$V_a = 4 \times 35 \times \frac{3.14}{4} \times 0.005^2 = 0.0027 \text{ m}^3/\text{s}$$

Velocity (V) in pipe having 4 cm diameter: It is the ratio of discharge through nozzles to area [Eq. (47.2)], which is expressed in metre per second (m/s).

$$V = \frac{Q_v}{A} \text{ or } \frac{V_a}{A} \quad (47.2)$$

where,

Q_v = discharge through nozzles (m^3/s)

A = area $\left(\frac{\pi r^2}{4}\right)$

Therefore, $$V = \frac{0.0027}{\frac{3.14 \times 0.04^2}{4}} = 2.15 \text{ m/s}$$

Friction loss (f_l): It is the ratio of friction factor, depth required and pipe velocity to the pipe diameter [Eq. (47.3)], which is expressed in metre (m).

$$f_l = 4 f_f \frac{d_r v^2}{d_p 2g} \quad (47.3)$$

where,

f_f = friction factor

d_r = depth required (m)

v = velocity through pipe (m/s)

d_p = diameter of the pipe (cm)

g = acceleration due to gravity (9.81 m/s^2)

Therefore, $$f_l = 4 \times 0.01 \times \left(\frac{90 \times 2.15^2}{0.04 \times 2 \times 9.81}\right) = 21.20 \text{ m}$$

Total head to be delivered by pump: It is the sum of depth required and friction factor [Eq. (47.4)], which is expressed in metre (m).

$$\text{Total head} = d_r + f_l \quad (47.4)$$
$$= 90 + 21.20 = 111.20 \text{ m}$$

Therefore, a pump of 2.7 l/s (0.0027 m^3/s) with a delivery head of 111 m is required.

PROBLEM 48 Using the given data, determine the (a) depth of irrigation, (b) irrigation interval (frequency), (c) total area irrigated and (d) number of watering days.

Key Concept Rainfall, contribution of soil moisture from the soil profile, and applied irrigation water are the sources of water requirements of crops. A part of the water applied to the irrigated fields for growing crops is lost in consumptive use and the balance infiltrates to recharge the groundwater. The process of re-entry of a part of the groundwater used for irrigation is called *return irrigation flow*. Infiltration from the applied irrigation water of both groundwater and surface water constitutes one of the major components of groundwater recharge in the areas under wet crops. Depending on the water pumping, consumptive use of water for crop, water allowed at the peak time of plant flowering stage, irrigation efficiency, soil moisture holding capacity and depth of effective root zone for crops, it can be possible to estimate the depth of irrigation, irrigation interval (frequency), total area irrigated and number of watering days.

Data of the given problem

Volume of water pumped per day = 1,500 lpm

Average daily consumptive use of water for crop = 3 mm

Allowing water at the peak time of plant flowering stage = 30% or 0.3

Irrigation efficiency for better water management and intensive irrigation = 65%

Soil moisture holding capacity per 30 cm depth of soil = 4.7 cm or 470 mm

Average depth of effective root zone for crops = 1 m

Seasonal consumptive use of water for crops = 45 cm

Solution

(a) Depth of irrigation (D_i): It is the ratio of soil moisture holding capacity to the water allowed at the peak time of plant flowing stage [Eq. (48.1)], which is expressed in centimetre (cm).

$$D_i = \frac{S_m}{P_p} \tag{48.1}$$

where,

S_m = soil moisture holding capacity (mm)

P_p = allowing water at the peak time of plant flowering stage (%)

Therefore, $$D_i = \frac{4.7 \times 100}{30} = 15.67 \text{ cm}$$

Generally, when the water is used to replenish the soil moisture, it can be depleted to 50% due to evapotranspiration.

$$\text{Then, the depth of application or irrigation} = \frac{15.67 \times 50}{100}$$

$$\text{Therefore, depth of application} = 7.84 \text{ cm}$$

$$\text{Depth of the application, as per the irrigation efficiency of } 65\% = \frac{7.84 \times 100}{65}$$

$$\text{Therefore, depth of application} = 12.06 \text{ cm}$$

(**b) Irrigation interval (frequency):** It is the ratio of depth of the irrigation to water usage at the peak time of plant flowering stage [Eq. (48.2)], which is expressed in days.

$$\text{Irrigation interval} = \frac{D_i}{P_u} \tag{48.2}$$

where,

D_i = depth of the irrigation (cm)
P_u = water use at the peak time of plant flowering stage = $3 + 3 \times 0.3 = 3.9$ mm

$$\text{Therefore, irrigation interval} = \frac{7.84 \times 10}{3.9} = 20.10 \quad \text{or} \quad 20 \text{ days}$$

(c) Total area irrigated: It is the ratio of the discharge to the depth of irrigation [Eq. (48.3)], which is expressed in hectare (ha).

$$\text{Area irrigated per day} = \frac{Q}{D_i} \tag{48.3}$$

where,

Q = discharge (lph)
D_i = depth of the application (cm)

$$\text{Area irrigated per day} = \frac{(1{,}500 \times 60 \times 12) \times 1{,}000}{12.06} = 0.89 \text{ ha}$$

Therefore, total area irrigated = Area irrigated per day × Irrigation interval = 0.89 × 20 = 17.8 ha

(**d) Number of watering days:** It is the ratio of the water consumption for crops to the depth of the irrigation [Eq. (48.4)]. This is expressed in days.

$$\text{Number of watering days} = \frac{D_c}{D_i} \tag{48.4}$$

where,

D_c = seasonal consumptive use of water for crops (cm)
D_i = depth of the irrigation (cm)

Therefore, $$\text{number of watering days} = \frac{45}{7.84} = 5.74 \text{ or } 6 \text{ days}$$

PROBLEM 49 The size of the stream of 50 lps can irrigate a border strip of 6 m × 225 m. The rate of infiltration of the soil is 3 cm/hour. The average depth of water flowing over the land is 6.5 cm. The soil moisture content before irrigation is 15%. The field capacity of the soil is 45%. The apparent specific gravity of the soil is 1.60. The period of the irrigation is 20 days. Estimate the (a) time of irrigation, (b) depth of penetration of water, (c) peak consumptive use of water and (d) maximum area that would be covered by the stream.

Key Concept Irrigation under the stream depends on many factors like the rate of infiltration of the soil, depth of water flowing over the land, soil moisture content before irrigation, field capacity of the soil, apparent specific gravity of the soil, period of the irrigation and time of irrigation. Thus, depending on of these factors, it is possible to estimate the depth of penetration of water, peak consumptive use of water and the maximum area covered by the stream.

Data of the given problem

Size of the stream = 50 lps or 0.050 × 60 × 60 m^3/hour
Boarder strip = 6 × 225 m
Rate of infiltration of the soil = 3 cm/hour
Depth of water flowing over the land = 6.5 cm
Soil moisture content before irrigation = 15%
Field capacity of the soil = 45%
Apparent specific gravity of the soil = 1.60
Period of the irrigation = 20 days

Solution

(a) Time of irrigation (*t*): It is the ratio of average depth of the water flowing over the land and rate of infiltration of soil to the area covered with water [Eq. (49.1)], which is expressed in time (*t*).

$$t = 2.303\frac{y}{I}\log_{10}\frac{q}{q - IA} \tag{49.1}$$

where,

t = necessary time to cover the strip (min)
y = average depth of the water flowing over the land (cm)
I = rate of infiltration of the soil (cm/hour)
q = size of the stream (m^3/hour)
A = area covered with water in time

Therefore,

$$t = 2.303\frac{6.5}{3}\log_{10}\frac{0.050 \times 60 \times 60}{0.050 \times 60 \times 60 - \frac{3}{100}(6 \times 225)}$$

$$t = 0.552 \text{ hour or } 33 \text{ min}$$

(**b) Depth of penetration (D_i):** It is the product of field capacity, moisture content and apparent specific gravity of soil, and depth of the effective root zone [Eq. (49.2)], which is expressed in centimetre (cm).

$$\text{Depth of water applied or depth of penetration } (D_i) = \frac{w_f - w_i}{100}G_m D \tag{49.2}$$

where,

w_f = field capacity of the soil (%)
w_i = moisture content of the soil (%)
G_m = apparent specific gravity of the soil
D = depth of the effective root zone (cm)

Then,

$$D_i = \frac{(45 - 15) \times 1.60D}{100} = 0.3D$$

Volume of water applied: It is the product of depth of the penetration and area covered with water which is equal to the size of the stream and time of the irrigation [Eq. (49.3)], and is expressed in centimetre (cm).

$$\text{Volume of water applied} = D_iA = qt \tag{49.3}$$

where,

D_i = depth of the penetration
A = area covered with water (border strip)
q = size of the stream (m^3)
t = time of the irrigation (hour)

Thus, volume of water applied = $0.3D\ (6 \times 225) = 0.05 \times 33 \times 60$

$\Rightarrow$ $405D = 99$

Therefore, depth of effective root zone, $D = \dfrac{99}{405} = 0.244$ m or 24.4 cm

(c) Peak consumptive use (p_c): It is the ratio of the depth of the irrigation to the period of irrigation [Eq. (49.4)], which is expressed in centimetre per day (cm/day).

$$p_c = \frac{D_i}{d_p} \tag{49.4}$$

where,
D_i = depth of the application
d_p = period of the irrigation (days)

Depth of application (D_i): It is the product of the soil moisture content, apparent specific gravity of the soil and depth of the penetration [Eq. (49.5)], which is expressed in centimetre (cm).

$$D_i = wG_mD \tag{49.5}$$

where,
w = soil moisture content
G_m = apparent specific gravity of the soil
D_i = depth of the penetration (cm)

Then, $D_i = 0.15 \times 1.60 \times 0.244 = 0.05856$ mm or 5.86 cm

Therefore, $p_c = \dfrac{5.86}{20} = 0.20$ cm/day

(d) Maximum area covering by the stream (A): It is the ratio of the stream size to the rate of infiltration of soil [Eq. (49.6)], which is expressed in square metre (m^2).

$$A = \frac{q}{I} \tag{49.6}$$

where,

q = size of the stream (m/hour)
I = rate of infiltration of the soil (cm/hour)

Therefore,
$$A = \frac{0.5 \times 60 \times 60}{0.03} = 6{,}000 \text{ m}^2$$

PROBLEM 50 Estimate the leaching requirement if the saturated soil solution (drainage water) and irrigation water have electrical conductivity of 9,000 μ mhos/cm and 850 μ mhos/cm measured at 25^{o}C, respectively. Also, determine the depth of water applied if the consumptive use of water for crop is 6 m.

Key Concept Leaching requirement is the amount of water applied to flush out of the root zone excess salts that are present in the soil, which are detrimental to crop production. It depends on the salt content of irrigation water, depth of reclamation and the soil properties. The minimum amount of water required to remove the salts from the root zone area is estimated using the ratio of the electrical conductivities of irrigation water (applied water) and drainage water (leaching requirement). Any amount of water in excess of the leaching requirement that goes to deep percolation is non-beneficial, and reduces water use efficiency at that scale.

Data of the given problem

EC of the saturated soil solution = 9,000 μ mhos/cm
EC of the irrigation water = 850 μ mhos/cm
Consumptive use of water for crop = 6 m

Solution

(a) Leaching requirement (*LR*): It is the ratio of the EC of irrigation water to the EC of drainage water [Eq. (50.1)], which is expressed in percentage (%).

$$LR = \frac{EC_i}{EC_d} \times 100 \tag{50.1}$$

where,

EC_i = EC of the irrigation water (μ mhos/cm)
EC_d = EC of the drainage water (μ mhos/cm)

Therefore,
$$LR = \frac{850}{9{,}000} \times 100 = 9.44\%$$

(b) Depth of water applied (D_i): It is the ratio of the consumptive use of water for crop to the leaching requirement [Eq. (50.2)], which is expressed in centimetre (cm).

$$D_i = \frac{D_c}{1 - LR} \tag{50.2}$$

where,

D_c = consumptive use of water for crop (m)
LR = leaching requirement (%)

Therefore,
$$D_i = \frac{6}{1 - \frac{9.44}{100}} = 6.63 \text{ cm}$$

8

Seawater Intrusion

PROBLEM 51 If the depth of water table near the coast is 1.5 m above mean sea level (amsl), determine the depth of the fresh water-salt water interface with neat sketch.

The densities of the fresh water and seawater are 1.000 g/cm^3 and 1.025 g/cm^3, respectively.

Key Concept Fresh groundwater is an important source of water supply in coastal areas. Knowing the temporal and spatial evolution of the fresh water-salt water interface is significant for groundwater development and prevention of seawater intrusion and for understanding the vulnerability of a coastal environment. Salt water occurs underground, not at the sea level, but at a depth below sea level which is of 40 times the height of the fresh water above the mean sea level, due to overexploitation of groundwater in coastal area. The estimation of depth of fresh water-salt water interface (40 times) is attributed to a hydrostatic equilibrium existing between the densities of fresh water and salt water. This relation is known as Ghyben–Herzberg relation.

Data of the given problem

Depth of the water table above mean sea level = 1.5 m

Density of the fresh water = 1.000 g/cm^3

Density of the sea water = 1.025 g/cm^3

Solution

Figure 51.1 shows the depth of the fresh water-salt water interface.

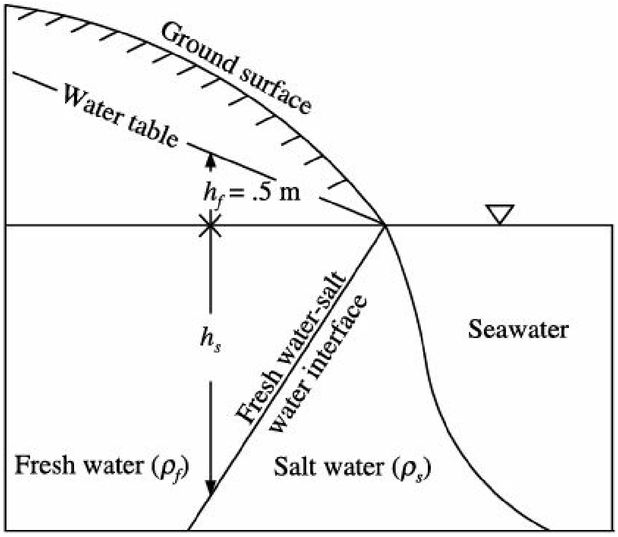


FIGURE 51.1 Fresh water-salt water interface.

Depth of the fresh water-salt water interface below sea level (h_s): It is the ratio of fresh water density to salt water density [Eq. (51.1)], which is expressed in metre (m).

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} \tag{51.1}$$

where,

ρ_f = density of the fresh water (g/cm^3)
ρ_s = density of the seawater (g/cm^3)
h_f = elevation of the water level above sea level (m)

Therefore, $$h_s = \frac{1.000}{1.025 - 1.000} \times 1.5 = 60 \text{ m}$$

PROBLEM 52 A well is located 6 km away from the coast. If the level of water table is 12 m amsl and the hydraulic conductivity of the aquifer is 15 m/day with a recharge of 4.5×10^{-4} m/day, determine the movement of the fresh water discharge from the inland aquifer towards the sea under equilibrium conditions, with neat sketch. The density of the fresh water is 1.000 g/cm^3 and the density of the seawater is 1.025 g/cm^3.

Key Concept In the coastal area, the rate of movement of freshwater discharge from the inland aquifer towards the sea depends on the recharge water, hydraulic conductivity of the aquifer material and the height of the water table above the mean sea level under equilibrium conditions of the fresh water-salt water interface.

Data of the given problem

Distance of the well from the sea coast = 6 km
Depth of the water table above sea level = 12 m
Hydraulic conductivity of the aquifer = 15 m/day
Recharge water = 4.5×10^{-4} m/day
Density of the fresh water = 1.000 g/cm^3
Density of the seawater = 1.025 g/cm^3

Solution

Figure 52.1 shows the movement of the fresh water discharge from the island aquifer towards the sea under equilibrium conditions.

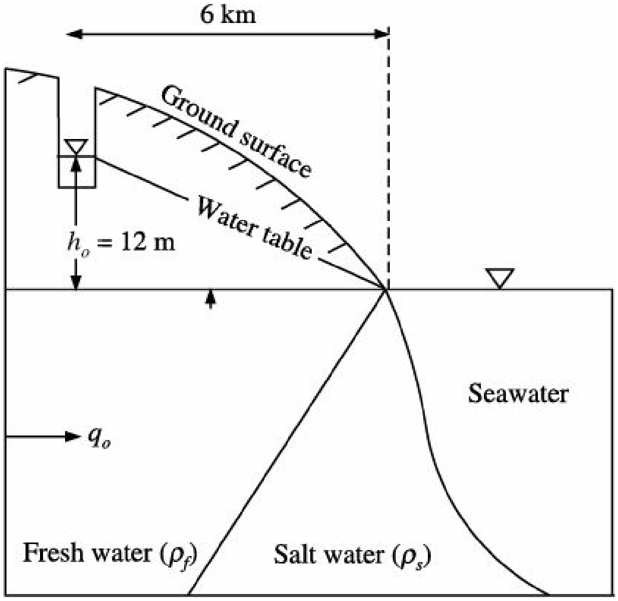


FIGURE 52.1 Movement of fresh water discharge from inland aquifer towards the sea under equilibrium conditions of fresh water-salt water interface.

Flow of groundwater through a water table aquifer recharged under uniform equilibrium condition (q_o): It is the ratio of the hydraulic conductivity, fresh water-salt water interface and recharge to the length of the fresh water body [Eqs. (52.1) and (52.2)]. It is expressed in cubic metre per day per kilometre length (m^3/day per km length).

$$h_o - h = \frac{2q_oL + WL^2}{k\left(1 + \dfrac{\rho_f}{\rho_s - \rho_f}\right)} \tag{52.1}$$

Then,

$$(q_o) = \frac{k\left[h_o^2\left(1 + \dfrac{\rho_f}{\rho_s - \rho_f}\right)\right] - WL^2}{2L} \tag{52.2}$$

where,

k = hydraulic conductivity of the aquifer (m/day)
h_o = depth of the water level above sea level (m)
ρ_f = density of the fresh water (g/cm^3)
ρ_s = density of the sea water (g/cm^3)
L = length of the fresh water body (km)
W = recharge (m/day)

Therefore,

$$q_o = \frac{15\left[12^2\left(1 + \dfrac{1.000}{1.025 - 1.000}\right)\right] - 4.5 \times 10^{-4} \times 6{,}000^2}{2 \times 6{,}000}$$

$$q_o = 0.603 \text{ m}^3\text{/day per km length}$$

PROBLEM 53 In a coastal aquifer of the island, the bottom of the well is 25 m above the fresh water-salt water interface. The hydraulic conductivity of the aquifer is 3 m/day and the fresh water-salt water interface is at a depth of 60 m below at a distance of 100 m inland from the shore. The height of equilibrium of saline water cone below the well centre is 15 m. To prevent the entering of saline water into the well, how much pumping rate of the well will be required? Explain with neat sketch.

Key Concept In the island area, the fresh water-salt water interface is horizontal at the start of pumping. With the continued pumping, the interface can rise successively to higher levels, until it reaches the well bottom. The phenomenon is called *upconing*. Then, the fresh water can degrade with salt water. When the pumping is stopped, the denser saline water tends to settle downward and returns to its original position. Thus, the optimum pumping rate is necessary to prevent the entering of saline water into fresh water aquifer system.

Data of the given problem

Depth of the fresh water-salt water interface below the well = 25 m
bottom prior to pumping

Hydraulic conductivity of the aquifer = 3 m/day

Depth of the fresh water-salt water interface below at a = 60 m
distance of 100 inland from the shore

Height of equilibrium of saline water cone below the well centre = 15 m

Solution

Figure 53.1 depicts the horizontal rise of fresh water-salt water interface after upconing in an island area.

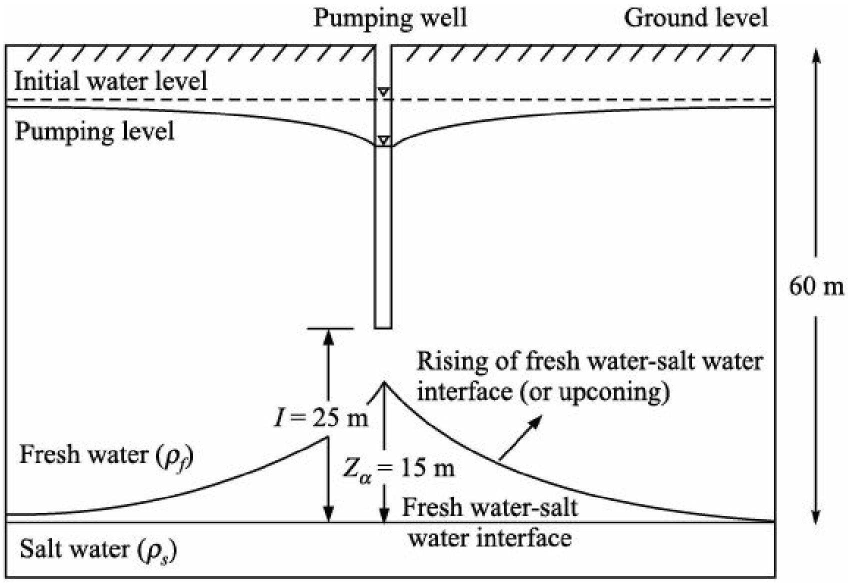


FIGURE 53.1 Horizontal rise of fresh water-salt water interface after upconing in an island area.

Pumping rate (*Q*): It is the product of the upconing, fresh water-sea water interface, hydraulic conductivity and depth of fresh water-salt water interface below well bottom prior to pumping [Eq. (53.1)], which is expressed in litre per minute (lpm).

$$Q = \frac{Z_\alpha . 2\pi(\rho_s - \rho_f)KL}{\rho_f} \tag{53.1}$$

where,

Z_α = ultimate or equilibrium height of saline water cone below the well centre or upconing, $\left(= \frac{\rho_f Q}{2\pi(\rho_s - \rho_f)KL}\right)$, (m)

ρ_f = density of the fresh water (1.000 g/cm^3)

Q = pumping rate of well (m^3/day)

ρ_s = density of the seawater (1.025 g/cm^3)

K = hydraulic conductivity (m/day)

L = depth of fresh water-salt water interface below well bottom prior to pumping (m)

Therefore,
$$Q = \frac{15 \times 2 \times 3.14\,(1.025 - 1.000) \times 3 \times 25}{1.000}$$

$$= 176.63 \text{ gallons per minute (gpm) or 790 lpm}$$

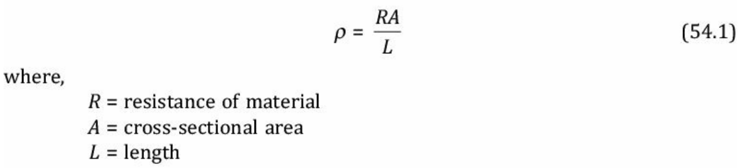
9

Groundwater Exploration

PROBLEM 54 The data (shown in Table 54.1) pertaining to the vertical electrical sounding (VES) carried out in a rocky terrain is obtained from the geoelectrical survey using Wenner configuration. Compute the geoelectrical parameters using the inverse slope method.

Key Concept Electrical resistivity (resistivity or specific electrical resistance or volume resistivity) is an intrinsic property which quantifies how strongly a given material opposes the flow of electric current. The unit of electrical resistivity is ohm metre (Ω m).

Electrical resistivity (ρ) is the ratio of resistance of material and cross-sectional area to length [Eq. (54.1)], which is expressed in ohm metre (Ω m).



$$\rho = \frac{RA}{L} \tag{54.1}$$

where,

R = resistance of material
A = cross-sectional area
L = length

Electrical resistivity survey has high resolution power to delineate sub-surface features as well as geological boundaries. All geological formations possess a property called *resistivity*, which determines the ease with which the electrical current flows through them. In this method (Figure 54.1), a current (C) transmits through the two current electrodes (metal rods) into the ground. Then, the potential (P) develops a circulation of this current into the ground that measures it through two potential electrodes (porous pots with copper sulphate solution).

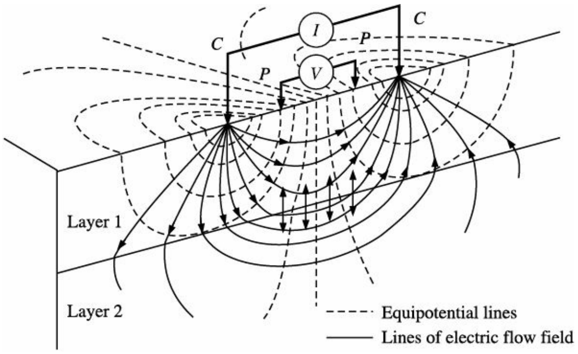


FIGURE 54.1 Electrical circuit for resistivity.

In Wenner array (Figure 54.2), the potential electrodes (ρ) are located in a line with the current electrodes (*C*), all four being equidistant (*a*) from one another and disposed symmetrically with respect to a central point. The depth of investigation in an isotropic and homogeneous formation is equal to the distance between any two electrodes. The apparent resistivity (ρ_a) in the Wenner arrangement is defined as the ratio of the distance between the adjacent electrodes and voltage difference between the potential electrodes to the applied current [Eq. (54.2)], which is expressed in ohm metre (Ω m).

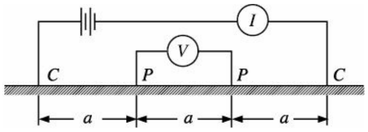


FIGURE 54.2 Wenner arrangement.

$$\rho_a = 2\pi a \frac{V}{I} \qquad (54.2)$$

where,

ρ_a = apparent resistivity (ohm m)
a = distance between the adjacent electrodes (m)
V = voltage difference between the potential electrodes
I = applied current

In addition to the curve matching technique used for the resistivity data interpretation from the Wenner soundings, a new method called *Inverse slope method* is also successfully used everywhere.

Data of the given problem

TABLE 54.1 VES Data

Electrode spacing (*a*) m	*Resistance* $\left(R = \frac{V}{I}\right)$	*Configuration constant* (2π *a*)	$\frac{1}{2\pi R}$ (mho)
1	6.56	6.28	0.024
2	2.48	12.56	0.064
3	2.35	18.84	0.068
5	2.12	31.40	0.075

7	1.94	43.96	0.082
9	1.59	56.52	0.100
12	1.36	75.36	0.117
15	1.13	94.20	0.141
18	0.95	113.04	0.168
21	0.91	131.88	0.175
24	0.87	150.72	0.190
27	0.82	169.56	0.194
30	0.76	188.40	0.210

Solution

Using the electrical resistivity survey, the resistance $\left(R=\frac{V}{I}\right)$ of the area is obtained, which varies from 0.76 to 6.56 (Table 54.1). The values of electrode spacing (a) are plotted on x-axis and the values of $\frac{1}{2\pi R}$ (mho) are plotted on y-axis on a simple arithmetic graph (Figure 54.3). The best fitting straight line segments passing through the plotted points are drawn and their intersections give the resistivity boundaries. The inverse slope of the segments gives the absolute resistivity of the corresponding layers (Table 54.2).

TABLE 54.2 The Results Obtained from Figure 54.3

Layer	*Depth* (m bgl)	*Thickness* (m)	*Resistivity* (ohm m)	*Expected geological unit*
1st	0 to 2	2	36.36	Soil zone
2nd	2 to 7.1	5.1	111.12	Weathered rock
3rd	7.1 to 17.9	10.8	142.86	Semi-weathered rock
4th	> 17.8	∞	252.44	Hard rock

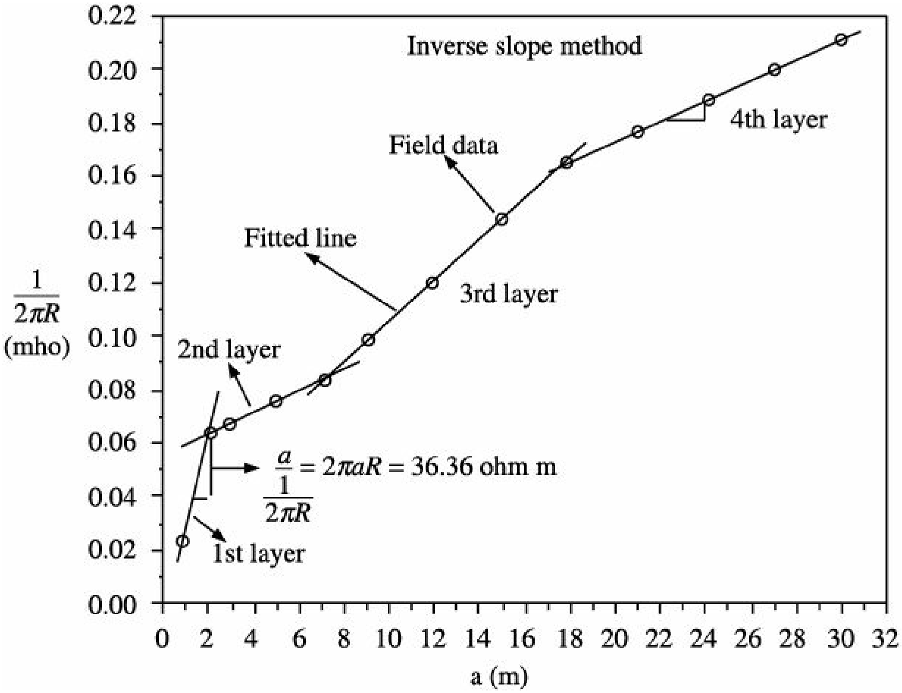


FIGURE 54.3 Plotting of the electrode spacing versus the value of $\frac{1}{2\pi R}$.

As per the results obtained from the interpretation of VES data (Figure 54.1 and Table 54.2), the rocky terrain shows four layers. The first layer (top soil) has a thickness of 2 m with a resistivity of 36.36 ohm m, indicating a low wet condition in it. The second layer (weathered zone) shows a thickness of 5.1 m, which has a resistivity of 111.12 ohm m. It indicates a limited water saturated condition. Similarly, the third layer (semi-weathered rock) also shows a water saturated body with a thickness of 10.8 m, as it has a resistivity of 142.86 ohm m. Finally, the fourth layer (hard rock portion) shows an indefinite thickness after semi-weathered rock zone. It has a resistivity of 252.44 ohm m. Thus, there is no possible condition of water occurrence from the four layer.

PROBLEM 55 The data of vertical electrical sounding (VES) (given in Table 55.1) carried out in a rocky terrain is obtained from the geoelectrical survey. Compute the true resistivity and corresponding thicknesses of the given data using Schlumberger configuration.

Key Concept Like Wenner method, the Schlumberger method is widely used for delineation of sub-surface geological features with respect to the occurrence of groundwater conditions. In this method, all four electrodes are placed in a line (Figure 55.1), but the distance (L) between the current electrodes (C) is maintained equal to or more than five times the distance (b) between the potential electrodes (P). In the Schlumberger arrangement, the *apparent resistivity* (ρ_a) is defined as the ratio of the distance between the adjacent electrodes and current and potential electrode spacing to the applied current [Eq. (55.1)], which is expressed in ohm metre (Ω m).

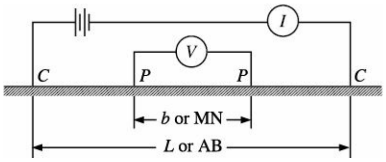


FIGURE 55.1 Schlumberger arrangement.

$$\rho_a = \pi a \frac{\left(\frac{L}{2}\right)^2 - \left(\frac{b}{2}\right)^2}{b} \frac{V}{I} \tag{55.1}$$

where,

ρ_a = apparent resistivity (ohm m)
a = distance between the adjacent electrodes (m)
L = current electrode spacing (or AB; m)
b = potential electrode spacing (or MN; m)
V = voltage difference between the potential electrodes
I = applied current

For obtaining the true resistivity (ρ) of the formations, the data of the apparent resistivity observed from the field should be matched with the type (master) curves of H, A, K and Q types (Appendix VI).

Data of the given problem

TABLE 55.1 VES Data

Electrode spacing (AB/2) m	*Apparent resistivity* (ρ_a) (ohm m)	*Electrode spacing* (AB/2) m	*Apparent resistivity* (ρ_a) (ohm m)
1	96.0	80	28.1
2	83.4	90	31.1
3	79.3	100	35.3
5	35.8	120	42.0
7	20.5	140	49.9
10	12.9	160	56.0
12	11.5	180	62.3
15	11.0	200	70.2

20	11.2	220	79.8
25	12.1	240	85.5
30	12.9	260	90.0
35	13.9	280	95.5
40	15.2	300	105.5
50	18.9	320	110.0
60	21.1	340	119.8
70	24.5	360	127.5

Solution

In the Schlumberger configuration, the observed apparent resistivity (ρ_a) varies from 11 ohm m to 127.5 ohm m (Table 55.1). The first step in this method is to plot the data of electrode spacing ($AB/2$) on x-axis and the apparent resistivity (ρ_a) on y-axis [Figure 55.2(a)] on a trace paper, which is superposed on double logarithmic graph. The second step is superpose the data of the trace paper on the master curve [Figure 55.2(b)] without any deviation in the coordinate axes of the two papers being held parallel and moved to a position that best fits the type curve [Figure 55.2(c)]. Then, fix the match point (+) and record its positions on coordinates. These values are then used to compute the resistivity (ρ) and thickness (h) as shown below (Table 55.2):

$$\frac{\rho_2}{\rho_1} = 0.1,\ \frac{\rho_3}{\rho_1} = \infty \text{ and } \frac{h_2}{h_1} = 15$$

Then, $\frac{\rho_2}{\rho_1}, \frac{\rho_3}{\rho_1}, \frac{h_2}{h_1}$ and $\frac{h_3}{h_1}$ are observed from the master curve.

TABLE 55.2 Results of the VES

Resistivity (ρ)	*Thickness* (h)
ρ_1= 97.8 ohm m	h_1 = 2 m
ρ_2/ρ_1 = 0.1 so that ρ_2 = 9.78 ohm m (0.1 × 97.8)	h_2/h_1 = 15 so that h_2 = 30 m (2 × 15)
ρ_3/ρ_1= ∞ so that ρ_3= ∞	h_3/h_1= ∞ so that h_3 = ∞

As per the results obtained from the interpretation of VES data (Figure 55.2 and Table 55.2), the rocky terrain shows three layers. The first layer (soil cover) shows a thickness of 2 m with a resistivity of 97.8 ohm m, which indicates a dry condition in it. The second layer (weathered zone) has a thickness of 30 m with a resistivity of 9.78 ohm m, indicating a saturated condition in it. The third layer (massive zone) shows an indefinite resistivity. Therefore, it has also indefinite thickness so that there is not any possible condition of water occurrence in it.

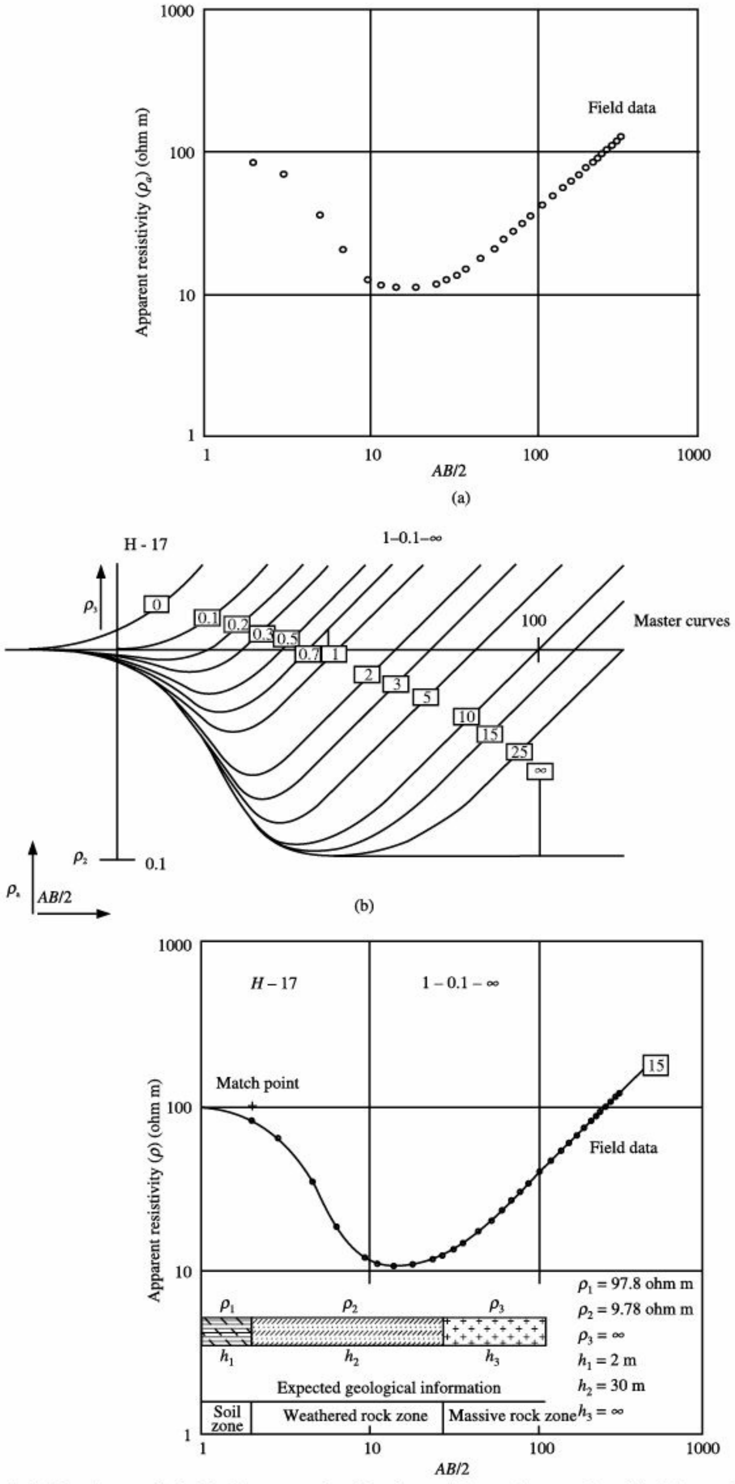


FIGURE 55.2 (a) Plotting of field data on double logarithmatic graph, (b) Three-layer *H*-type master curve of Orellana and Mooney, and (c) Matching of filed data with master curve.

10

Groundwater Quality

PROBLEM 56 Chemical composition of groundwater of an area (Figure 56.1) is shown in Table 56.1. From this, (a) compute the ionic-balance-error and (b) describe the spatial distribution of pH, EC, TDS, TA, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}, NO_3^- and F^-.

Key Concept Quality of the groundwater is as important as its quantity. It is a measure of the condition of water relative to its importance in the planning and any developmental activities because it allows the development of conceptual, statistical, analytical and numerical models of the groundwater system, which, in turn, helps in understanding how this system works and provides a means for predicting system responses to future conditions. Further, the spatial distribution of the quality of groundwater gives broad scenario about the possible sources and causes of the geogenic, anthropogenic and marine activities, which cause contamination.

Data of the given problem

TABLE 56.1 Chemical Composition of Groundwater

Chemical variables	*Sample numbers*					
	1	2	3	4	5	6
Temperature (°C)	21	20	23	23	24	26
Colour (HU)	2	2	3	6	7	7
Odour	–	–	–	–	Light bad	Bad
Taste	–	–	–	Brackish	Brackish	Brackish
Turbidity (JTH)	1	5	1	1	2	6
pH	8.2	8.3	8.0	7.9	7.8	6.8
Electrical conductivity, EC (μS/cm)	840	1,500	1,800	2,500	3,120	3,680
Total dissolved solids, TDS (mg/l)	546	975	1,170	1,625	2,028	2,390
Total alkalinity, TA (mg/l) as $CaCO_3$	361	468	172	185	369	193
Total hardness, TH (mg/l) as $CaCO_3$	298	529	244	488	595	604
Carbonate hardness, CH (mg/l)	298	468	172	185	369	193

Non-carbonate hardness, NCH (mg/l)	–	61	72	303	230	411
Excess alkalinity, EA (mg/l)	63	–	–	–	–	–
Calcium, Ca^{2+} (mg/l)	70	80	40	80	100	110
Magnesium, Mg^{2+} (mg/l)	30	80	35	70	85	80
Sodium, Na^{+} (mg/l)	55	91	291	330	430	542
Potassium, K^{+} (mg/l)	1	9	19	27	22	39
Bicarbonate, HCO_3^- (mg/l)	440	520	210	225	450	235
Carbonate, CO_3^{2-} (mg/l)	–	25	–	–	–	–
Chloride, Cl^- (mg/l)	15	85	225	460	715	950
Sulphate, SO_4^{2-} (mg/l)	23	120	365	243	126	243
Nitrate, NO_3^- (mg/l)	9	26	31	233	55	72
Fluoride, F^- (mg/l)	1.0	1.7	0.8	1.1	1.2	0.9

Note: Sample 1 is located nearby stream bed; sample 2 is away from stream bed; sample 3 is near drainage wastes; sample 4 is very close to drainage wastes, leakage of septic tank and irrigation land; sample 5 is close to irrigation land and, sample 6 is nearby industrial effluents and irrigation land.

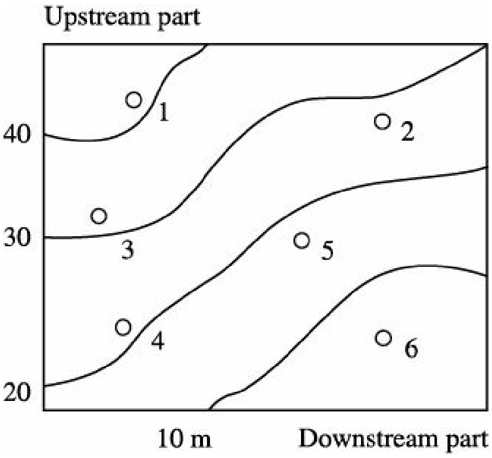


FIGURE 56.1 Location of the samples with contour elevations (m amsl).

Solution

(a) Computation of ionic-balance-error (IBE): For interpretation of the chemical analysis of water, it is essential to compute the ionic-balance-error [IBE; Eq. (56.1)], expressing the concentrations of ions in milliequivalent per litre (meq/l) by converting their concentrations from milligram per litre (mg/l; Table 56.2). The difference between the total cations ($Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}$) and total anions ($HCO_3^{-}$ + CO_3^{2-} + Cl^{-} + SO_4^{2-} + NO_3^{-} + F^{-}) should be within the acceptable limit of ±10% for the interpretation of data for any purpose from the hydrogeochemical point of view.

$$IBE = \frac{(TCC + TCA)}{(TCC - TCA)} \times 100 \tag{56.1}$$

where,

TCC = total concentration of cations

TCA = total concentration of anions

TABLE 56.2 Conversion Factors from mg/l to meq/l

Ion	*Factor*
Bicarbonate HCO_3^{-}	0.01639
Calcium (Ca^{2+})	0.04990
Carbonate CO_3^{2-}	0.03333
Chloride (Cl^{-})	0.02821
Fluoride (F^{-})	0.05264
Magnesium (Mg^{2+})	0.08226
Nitrate NO_3^{-}	0.01613
Potassium (K^{+})	0.02557
Sodium (Na^{+})	0.04350
Sulphate SO_4^{2-}	0.02082

$$\text{Conversion of concentration of ion from mg/l to meq/l} = \text{Concentration of the ion (mg/l)} \times \text{factor} \tag{56.2}$$

For example, Ca^{2+} in sample 1 = 70 × 0.04990

= 3.493 meq/l

TABLE 56.3 Conversion of Chemical Variables from mg/l to meq/l

Chemical variables	*Sample numbers*					
	1	2	3	4	5	6
Ca^{2+}	3.493	3.992	1.996	3.992	4.990	5.489
Mg^{2+}	2.468	6.581	2.879	5.758	6.992	6.581
Na^{+}	2.393	3.959	12.659	14.355	18.705	23.577

K^+	0.026	0.230	0.486	0.690	0.563	0.997
TCC	**8.380**	**14.762**	**18.020**	**24.795**	**31.250**	**36.644**
HCO_3^-	7.212	8.523	3.442	3.688	7.376	3.852
CO_3^{2-}	–	0.833	–	–	–	–
Cl^-	0.423	2.398	6.347	12.977	20.170	26.800
SO_4^{2-}	0.479	2.498	7.599	5.059	2.623	5.059
NO_3^-	0.145	0.419	0.500	3.758	0.887	1.161
F^-	0.053	0.089	0.042	0.058	0.063	0.047
TCA	**8.312**	**14.760**	**17.930**	**25.540**	**31.119**	**36.919**
IBE	0.25%	0.15%	0.40%	–0.68%	–0.20%	–0.27%

All the groundwater samples show IBE within the acceptable limit of ± 10% (Table 56.3). Thus, these data can be used for the interpretation of quality of groundwater for any purpose.

Temperature: The Earth's temperature affects the usefulness of water for many purposes. Most of the users desire water of uniformly low temperature. In general, the temperature of shallow groundwater shows some seasonal fluctuation, whereas the temperature of groundwater from moderate depths remains near or slightly above the mean annual air temperature of the area. In deep wells, the water temperature generally increases ١°C for each ٢٠ to ٣٠ m of depth. If there is an abnormal temperature, it indicates the existence of radioactive minerals in the sub-surface.

Temperature in the groundwater varies from 20°C (sample 2) to 26°C (sample 6; Table 56.1), which is the normal temperature.

Colour: *Colour* refers to the appearance of water that is free of suspended matter. It results almost entirely from the extraction of colouring matter and decaying organic materials such as roots and leaves in the bodies of surface water or in the ground. Natural colour of 10 Hazen units (HU) or less usually goes unnoticed, and even in larger amounts, is harmless in drinking water. Colour is objectionable when used in water for many industrial purposes. However, it may be removed from water by coagulation, sedimentation, and activated carbon filtration.

In the present groundwater samples, colour varies from 2 HU to 7 HU (Table 56.1) so that it is within the range of 10 HU of natural colour.

Taste and odour: Taste and odour are the human perceptions of water quality. Human perception of taste includes sour (hydrochloric acid), salty (sodium chloride), sweet (sucrose) and bitter (caffeine). Relatively simple compounds produce sour and salty tastes. However, sweet and bitter tastes are produced by more complex organic compounds. Whereas, an odour (or fragrance) is caused by one or more volatilised chemical compounds. Generally, humans or other animals can perceive the sense of olfaction, even at a very low concentration. Odours are commonly called *scents*, which refer to both pleasant and unpleasant odours. Its unit is European Odour Unit (OUE).

No taste is present in the groundwater samples 1 to 3, while the rest of the samples from 4 to 6 have brackish taste. Only groundwater samples 5 and 6 have light and bad odour (Table 56.1).

Turbidity: Water turbidity is attributable to suspended matter such as clay, silt, fine fragments of organic matter, and similar material. It shows up as a cloudy effect in water, and for this reason alone, it is objectionable in domestic and many industrial water supplies. It is expressed in Jackson turbidity units (JTU). Filtered water is free from noticeable turbidity. Unfiltered supplies, including those that contain enough iron for appreciable precipitation on exposure to air, may show turbidity. In surface water supplies, turbidity is usually a more variable quantity than dissolved solids. The turbidity (JTU) is from 1 (samples 1, 3, and 4) to 6 (samples 6; Table 56.1).

pH: Power of hydrogen (pH) is a negative logarithm of hydrogen ion concentration in moles per litre. The pH plays a vital role to react with acidic or alkaline material. It is controlled by $CO_2 - CO_3^{2-} - HCO_3^-$ equilibrium. The combination of CO_2 with H_2O (water) forms H_2CO_3 (carbonic acid), which affects the pH of water (Eqs. 56.3 to 56.5).

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \tag{56.3}$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \tag{56.4}$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-} \tag{56.5}$$

Water can be classified as acidic and alkaline on the basis of pH, which varies from 1 to 14 (Table 56.4). If water shows pH from 1 to 7, it is in acidic condition due to abundance of H^+ over OH^-. When the pH of water is 7, it denotes equal contents of H^+ and OH^-. If water has pH more than 7 (up to 14), it indicates alkaline water due to abundance of OH^- over H^+.

The pH varies from 6.8 (sample 6) to 8.3 (sample 2) in the groundwater (Table 56.1). As per the classification of pH (Table 56.4), the water is characterised by an alkaline condition, as OH^- is more than H^+ in water. Spatial distribution of pH shows that it is less than 7 in the south-eastern side and is more than 8 in the north and south-western sides (Figure 56.2). It suggests the controlling of topography over it.

TABLE 56.4 Classification of pH

pH range	*Type*	*Dominance of ions*	*Sample numbers*
1 to 7	Acid	H^+ is more than OH^-	–
7	Neutral	Equal amounts of H^+ and OH^-	–
7 to 14	Basic	OH^- is more than H^+	1 to 6

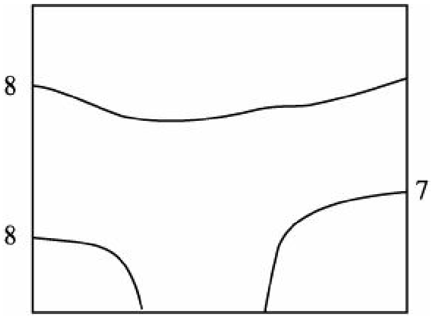


FIGURE 56.2 Spatial distribution of pH.

Electrical conductivity (EC): The EC is a measure of a material's ability to conduct electric current and is expressed in microsiemens per centimetre (μS/cm) at 25°C. The weak acids (HCO_3^- and CO_3^{2-}) have low conductivity, while the strong acids (Cl^-, SO_4^{2-} and NO_3^-) show high conductivity. The higher the EC, the greater is the enrichment of salts in water. Thus, the EC can be classified as Type I, if the enrichments of salts are low ($EC < 1,500$ μS/cm); as Type II, if the enrichment of salts are medium ($EC = 1,500$ and 3,000 μS/cm); and as Type III, if the enrichments of salts are high ($EC > 1,500$ μS/cm; Table 56.5).

Generally, the low EC is associated with the area of low interaction of water with aquifer materials due to high runoff and low infiltration of recharge water at topographic highs. The high EC is associated with the area of discharge water caused by longer contact of water in aquifer materials due to low runoff and high infiltration of water at topographic lows, in addition to the impact of anthropogenic origin.

TABLE 56.5 Classification of EC (Subba Rao et al., 2011)

EC range (μS/cm)	*Type*	*Enrichment of salts*	*Topography*	*Runoff*	*Infiltration*	*Water type*	*Sample numbers*
< 1,500	I	Low	High	High	Low	Recharge water	1 and 2
1,500 to 3,000	II	Medium	Moderate	Medium	Medium	–	3 and 4
> 3,000	III	High	Low	Low	High	Discharge water	5 and 6

The EC is in the range of 840 μS/cm (sample 1) to 3,680 μS/cm (sample 6) in the groundwater (Table 56.1). According to the classification of EC (Table 56.5), the groundwater samples 1 and 2 come under type I (low enrichment of salts), samples 3 and 4 come under type II (medium enrichment of salts), and samples 5 and 6 come under type III (high enrichment of salts). Spatial distribution of EC is shown in Figure 56.3. Low EC (< 1,000 μS/cm) is observed from the north-western side and high EC (> 3,500 μS/cm) from the south-eastern side with its progressive increase. This variation is a result of differences in rock-water interaction and anthropogenic sources in relation to topography as well as runoff and infiltration of recharge water.

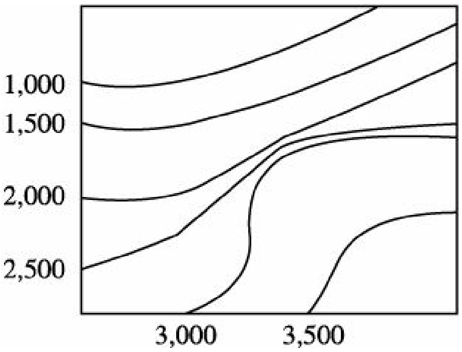


FIGURE 56.3 Spatial distribution of EC (μS/cm).

Total dissolved solids (TDS): The total dissolved solids (TDS) indicate the total salt concentration of dissolved ions from soils and rocks (including any organic matter and some water of crystallisation) in water and is expressed in milligrams per litre (mg/l). The amount and character of dissolved solids depend on the solubility and type of rocks with which the water has been in contact. Generally, low TDS is caused by the influence of rock-water interaction in relation to recharge water at topographic highs, and high TDS is due to impact of anthropogenic origin with respect to discharge water at topographic lows. The classification of TDS is shown in Table 56.6.

The value of TDS ranges from 546 mg/l (sample 1) to 2,390 mg/l (sample

6; Table 56.1). Groundwater quality in samples 1 and 2 come under fresh water category and that in samples 3 to 6 come under brackish category (Table 56.6). Very low TDS (< 500 mg/l) is observed from the north-western side, while very high TDS is observed from the south-eastern side, with its gradual increase (Figure 56.4). Generally, low TDS is caused by the influence of rock-water interaction in relation to recharge water at topographic highs, and high TDS is due to entering of foreign matter into the aquifer system with respect to discharge water at topographic lows.

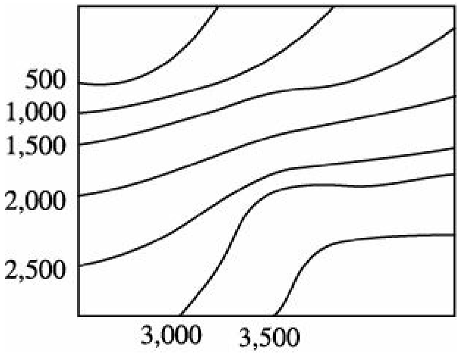


FIGURE 56.4 Spatial distribution of TDS (mg/l).

TABLE 56.6 Classification of TDS (Fetter, 1990)

TDS range (mg/l)	*Classification*	*Sample numbers*
< 1,000	Fresh	1 and 2
1,000 to 10,000	Brackish	3 to 6
10, 000 to 1,00,000	Saline	–
> 1,00,000	Brine	–

Total alkalinity (TA): Total alkalinity (TA) is a measure of the capacity of water to neutralise acid in terms of calcium carbonate ($CaCO_3$). It is mainly caused by OH^-, HCO_3^- and CO_3^{2-} ions, which may be ranked in order of their association with high pH values. If the pH is more than 8.2, the water is mainly characterised by HCO_3^- and CO_3^{2-}, and if it is less than 8.2, the water is mainly characterised by HCO_3^-.

The TA is in between 172 mg/l (sample 3) to 468 mg/l (sample 2; Table 56.1). This is mainly caused by HCO_3^- in the groundwater samples 1 and 3 to 6, as pH is less than 8.2, while it is caused by both HCO_3^- and CO_3^{2-} in the groundwater sample 2, as pH is more than 8.2. The spatial distribution of the

TA is high (> 400 mg/l) in the north-eastern side and low (> 200 mg/l) in the south-western side (Figure 56.5). It suggests the prevailng condition of alkalinity in the north-eastern side.

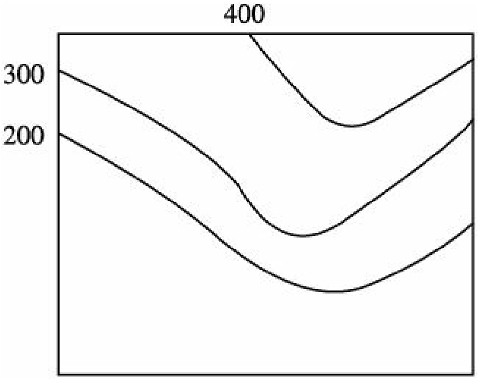


FIGURE 56.5 Spatial distribution of TA (mg/l).

Total hardness (TH): Total hardness (TH) as $CaCO_3$ is a measure of Ca^{2+} and Mg^{2+} of weak acids (HCO_3^- and CO_3^{2-}) and strong acids (Cl^- and SO_4^{2-}). All of the metallic cations other than the alkali metals deposit soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. The higher the TH, the greater is the soap lather. The classification of TH is shown in Table 56.7.

The TH ranges from 244 mg/l (sample 3) to 604 mg/l (sample 6; Table 56.1). According to the TH classification (Table 56.6), the groundwater samples 1 and 3 belong to hard category (150 mg/l to 300 mg/l), while samples 2 and 4 to 6 come under very hard category (> 300 mg/l). Spatial distribution of TH shows that the TH is less than 300 mg/l in the north-western side and is more than 600 mg/l in the south-eastern (Figure 56.6) due to increase in the impact of anthropogenic activities from the former side towards the latter side.

TABLE 56.7 Classification of TH (Davis and Dewiest, 1966)

TH range (mg/l)	*Classification*	*Sample numbers*
< 75	Soft	–
75 to 150	Moderately hard	–
150 to 300	Hard	1 and 3
> 300	Very hard	2 and 4 to 6

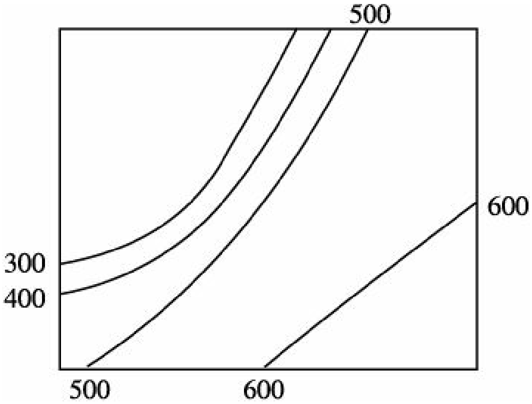


FIGURE 56.6 Spatial distribution of TH (mg/l).

Relation between TA and TH: Based on TA and TH, the water can be classified into three types—carbonate hardness (CH), non-carbonate hardness (NCH), and excess alkalinity (EA) (Table 56.8). The criterion followed is given below:

i. The values that are the lowest (among TA and TH) are placed under CH or *temporary hardness*.
ii. When the value of TA is greater than TH, the difference (TA – TH) value is considered as EA.
iii. When TH is more than TA, the difference value (TH – TA) is considered as NCH or *permanent hardness*.

The CH is characterised by Ca^{2+} and Mg^{2+} of HCO_3^- and CO_3^{2-} ions; the NCH is characterised by Ca^{2+} and Mg^{2+} of Cl^- and SO_4^{2-} ions, and the EA is characterised by Na^+ of HCO_3^- ions. The CH can be easily removed by boiling water due to presence of weak acids (HCO_3^- and CO_3^{2-}), whereas the NCH cannot be easily removed as CH from water due to presence of strong acids (Cl^- and SO_4^{2-}).

TABLE 56.8 Classification of CH, NCH and EA

Classification of CH, NCH and EA	*Concentration* (mg/l)	
TA	240	185
TH	165	290
CH	165	185
NCH	–	105

EA	75	–

The CH varies from 172 mg/l (sample 3) to 468 mg/l (sample 2) in the groundwater samples (1 to 6), whereas the NCH varies from 61 mg/l (sample 2) to 411 mg/l (sample 6) in the groundwater samples (2 to 6). The EA is observed in only one sample i.e., sample 1, which is 63 mg/l (Table 56.1). The CH can be removed by processes such as boiling or lime softening and then separation of water from the resulting precipitate, whereas the NCH cannot be easily removed as CH. The EA is caused by sodium bicarbonate ($NaHCO_3$).

Calcium (Ca^{2+}): Calcium (Ca^{2+}) is a major source of most igneous, sedimentary and metamorphic rocks. Minerals like plagioclase, pyroxene and amphiboles and rocks like limestone, dolomite, gypsum, anhydrite, sandstone and shale are the source of Ca^{2+} in the groundwater. The presence of carbon dioxide in the soil zone is another source of calcium in the groundwater. Ion exchange is also the source of calcium.

Ca^{2+} varies from 40 mg/l (sample 3) to 110 mg/l (sample 6; Table 56.1). Calcium feldspars present in the country rocks are the source of Ca^{2+} in the groundwater. Spatial distribution of Ca^{2+} is shown in Figure 56.7. Less than 70 mg/l Ca^{2+} is observed from the north-western side and it is more than 90 mg/l in the south-eastern side due to difference in the impacts of geogenic source on the groundwater system.

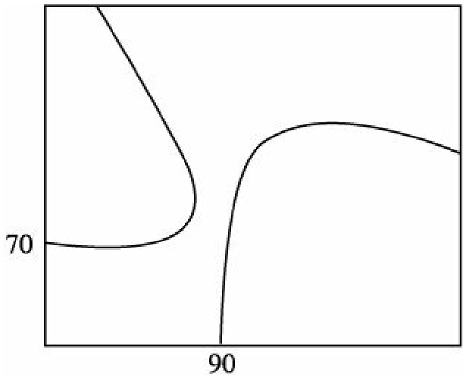


FIGURE 56.7 Spatial distribution of Ca^{2+} (mg/l).

Magnesium (Mg^{2+}): Magnesium (Mg^{2+}) is an important component of basic igneous rocks (dunites, pyroxenites and amphibolites), volcanic rocks (basalts), metamorphic rocks (talc, tremolite-schists), and sedimentary rocks (dolomite). Minerals like olivine, augite, biotite, hornblende, serpentine, etc. are the source of magnesium in the groundwater. The presence of carbon dioxide in the soil zone is another source of calcium in the groundwater. Seawater, mining activities and industrial effluents are also the source of magnesium in the groundwater.

The Mg^{2+} varies from 30 mg/l (sample 1) to 80 mg/l (samples 2 and 6; Table 56.1). Geogenic source (ferromagnesium minerals) and anthropogenic activities appear as the source of Mg^{2+} in the groundwater (Appendix XIII). Low concentration of Mg^{2+} (less than 30 mg/l) is observed from the north-western side, while it is more than 70 mg/l in the south-eastern side (Figure 56.8) due to difference in the influences of geogenic and anthropogenic sources on the groundwater body.

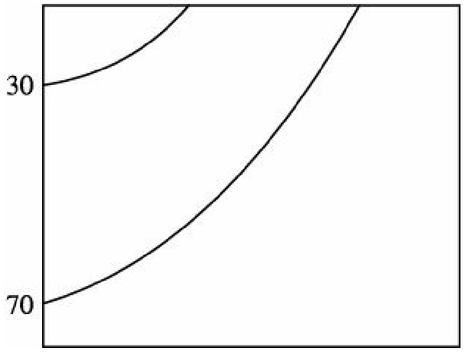


FIGURE 56.8 Spatial distribution of Mg^{2+} (mg/l).

Sodium (Na^+): Weathering of the plagioclase feldspars, nepheline, sodalite, glaucophane and aegirine are the sources of sodium (Na^+) in the groundwater. Clay minerals and zeolites are also the sources of sodium. Ancient brines, seawater, industrial effluents and municipal waste waters increase the concentration of sodium in the groundwater. Ion exchange process can increase the sodium content in the groundwater. Sodium salts are readily soluble in the groundwater.

The Na^+ ranges from 55 mg/l (sample 1) to 542 mg/l (sample 6; Table 56.1). Sodium feldspars and anthropogenic activities are the main sources of Na^+ in the groundwater. Spatial distribution of Na^+ shows that Na^+ is less than 100 mg/l in the northern side and is more than 500 mg/l in the southern side (Figure 56.9) due to progressive increase in anthropogenic source over geogenic origin.

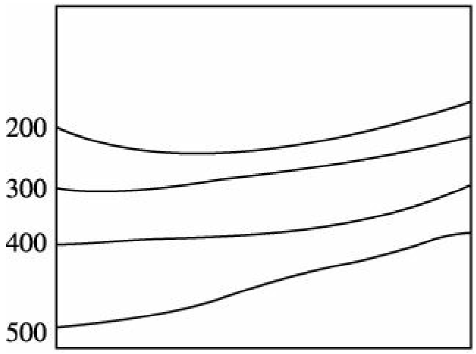


FIGURE 56.9 Spatial distribution of Na^+ (mg/l).

Potassium (K^+): Important sources of the potassium (K^+) include orthoclase feldspars, nepheline, leucite and biotite. Chemical fertilisers are the other sources of potassium. Generally, lower content of potassium is caused by its absorption on clay minerals.

The K^+ is in between 1 mg/l (sample 1) and 39 mg/l (sample 6; Table 56.1), with an increasing trend from the northern side (less than 10 mg/l) to the south-eastern side (more than 30 mg/l; Figure 56.10) due to influence of anthropogenic activities on the groundwater system.

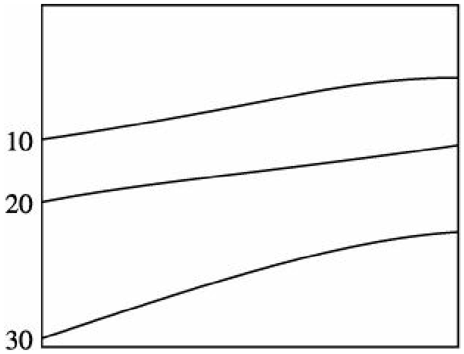


FIGURE 56.10 Spatial distribution of K^+ (mg/l).

Bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}): Dissolved carbon dioxide (CO_2) present in the rainwater as well as in the soil cover is the main source of carbonates [bicarbonate, (HCO_3^-) and carbonate, (CO_3^{2-})] in the groundwater, depending on the increase in temperature and decrease in pressure. Decay of the organic matter also releases carbon dioxide for dissolution. When the pH is more than 8.2, HCO_3^- dissociate as CO_3^{2-}.

The HCO_3^- varies from 210 mg/l (sample 3) to 520 mg/l (sample 2; Table

56.1). Soil CO_2 is the main source of HCO_3^- in the groundwater. Spatial distribution of HCO_3^- shows that it is less than 300 mg/l in the south-western side and is more than 500 mg/l in the north-eastern side (Figure 56.11) due to prevailing condition of alkalinity.

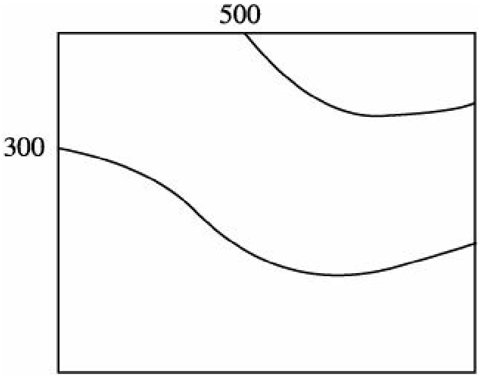


FIGURE 56.11 Spatial distribution of HCO_3^- (mg/l).

Chloride (Cl^-): Chloride (Cl^-) is dissolved from rocks and soils. Present in sewage and found in large amounts in ancient brines, seawater, and industrial brines, domestic waste waters, septic tanks, large quantities increase the corrosiveness of water and, in combination with Na^+, they give a salty taste. The chlorides of Ca^{2+}, Mg^{2+}, Na^+ and K^+ are readily soluble. Drainage from salt springs and sewage, oil fields, and other industrial wastes may add large amount of Cl^- to the streams and groundwater reservoirs.

The Cl^- varies from 15 mg/l (sample 1) to 950 mg/l (sample 6; Table 56.1). Non-lithological origin (domestic waste water, industrial effluents, etc.) is the main source of Cl^- in the groundwater. Low Cl^- (< 250 mg/l) is observed from the north-western side and more than 750 mg/l is observed from the south-eastern side (Figure 56.12) due to progressive increase in anthropogenic activity on the groundwater system.

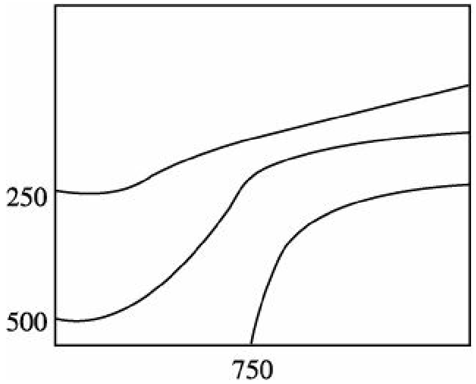


FIGURE 56.12 Spatial distribution of Cl^- (mg/l).

Sulphate (SO_4^{2-}): Sulphate (SO_4^{2-}) is dissolved from rocks containing gypsum, iron sulphides, and other sulphur compounds. It is commonly present in mine water and in some industrial wastes.

The SO_4^{2-} varies from 23 mg/l (sample 1) to 365 mg/l (sample 3; Table 56.1). Non-lithological origin (domestic waste water, industrial effluents, etc.) appears as the main source of SO_4^{2-} in the groundwater. Low SO_4^{2-} (< 150 mg/l) is observed from the north-western side and it is more than 300 mg/l in the south-eastern side (Figure 56.13) due to progressive increase in anthropogenic activity.

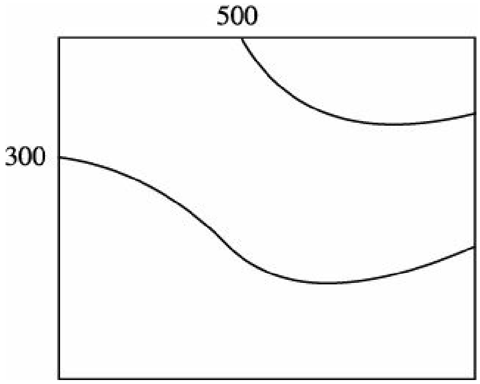


FIGURE 56.13 Spatial distribution of SO_4^{2-} (mg/l).

Nitrate (NO_3^-): The sources of nitrate (NO_3^-) are decaying organic matter, legume plants, sewage, nitrate fertilisers, and nitrates in soil. Nitrate encourages the growth of algae and other organisms, which cause undesirable tastes and odours. Concentration of more than 10 mg/l indicates pollution. Nitrates in water may indicate sewage or other organic matter.

The NO_3^- varies from 9 mg/l (sample 1) to 233 mg/l (sample 4; Table 56.1). Domestic waste water, chemical fertilisers, etc. appear as the main source of NO_3^- in the groundwater. If NO_3^- is more than 10 mg/l, it indicates man-made pollution. Low NO_3^- (< 10 mg/l) is observed from the north-western side and it is more than 90 mg/l in the south-western side (Figure 56.14) due to progressive increase in anthropogenic activity.

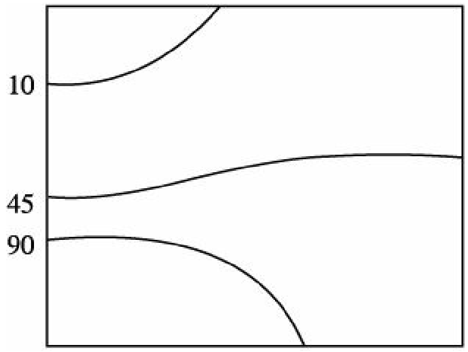


FIGURE 56.14 Spatial distribution of NO_3^- (mg/l).

Fluoride (F^-): Important sources of fluoride (F^-) in the groundwater are fluoride-bearing minerals like fluorite, apatite, biotite and hypersthene. Clay minerals also contribute fluoride to the groundwater. Agriculture fertilisers can also increase the content of fluoride in the groundwater.

The F^- varies from 0.8 mg/l (sample 3) to 1.7 mg/l (sample 2; Table 56.1). Geogenic and anthropogenic sources (chemical fertilisers) are the main source of F^- in the groundwater. Low F^- (< 1.0 mg/l) is observed from the south-western side and it is more than 1.5 mg/l in the north-eastern side (Figure 56.15) due to prevailing condition of alkalinity.

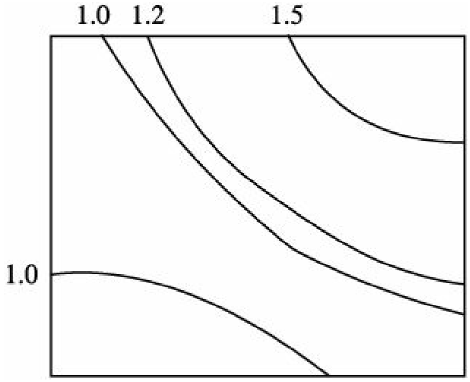


FIGURE 56.15 Spatial distribution of F^- (mg/l)

PROBLEM 57 From Table 57.1, (a) delineate the recharge and discharge areas, using the hydrogeochemical facies and genetic classification, (b) evaluate the groundwater quality, using the Piper's diagram and (c) classify the mechanisms that control the groundwater quality, using Gibb's as well as Langelier and Ludwig's diagrams, and (d) interpret the geochemical signatures and chloro-alkaline indices.

Key Concept The chemical composition of the groundwater can be used (a) to delineate the recharge and discharge areas on the basis of hydrogeochemical facies and genetic classification, which explain the distribution and genesis of principal groundwater types along water flow paths, (b) to evaluate the progressive changes in the geochemical characters of the groundwater, using Piper's trilinear diagram, (c) to assess the factors that control the origin of groundwater quality, using Gibb's as well as Langelier and Ludwig's diagrams, and (d) to measure the origin of water on the basis of the geochemical ratios and chloro-alkaline indices. This information clearly gives the sources and causes of groundwater contamination.

Data of the given problem

TABLE 57.1 Chemical Composition of Groundwater

Chemical variables	*Sample numbers*					
	1	2	3	4	5	6
Temperature (°C)	21	20	23	23	24	26
pH	8.2	8.3	8.0	7.9	7.8	6.8
Total dissolved solids, TDS (mg/l)	546	975	1,170	1,625	2,028	2,390
Calcium, Ca^{2+} (mg/l)	70	80	40	80	100	110
Magnesium, Mg^{2+} (mg/l)	30	80	35	70	85	80
Sodium, Na^{+} (mg/l)	55	91	291	330	430	542
Potassium, K^{+} (mg/l)	1	9	19	27	22	39
Bicarbonate, HCO_3^- (mg/l)	440	520	210	225	450	235
Carbonate, CO_3^{2-} (mg/l)	–	25	–	–	–	–
Chloride, Cl^- (mg/l)	15	85	225	460	715	950
Sulphate, SO_4^{2-} (mg/l)	23	120	365	243	126	243
Nitrate, NO_3^- (mg/l)	9	26	31	233	55	72
Fluoride, F^- (mg/l)	1.0	1.7	0.8	1.1	1.2	0.9

(a) Delineation of recharge and discharge areas

Hydrogeochemical facies (Seaber, 1962; Back, 1966): Hydrogeochemical facies explain the distribution and genesis of principal groundwater types along the water flow paths. The facies also provide information on progressive ion enrichment during stay of groundwater on the basis of residence time of water in sub-surface and the extent of rock-water interaction. The facies are arranged by taking the ionic percentages in relative decreasing order of their abundances and neglecting less than 5% of the total concentration of ions as insignificant (Tables 57.2 and 57.3). The facies can be classified with respect to residence time of water in aquifer material and topography, as shown in Table 57.4.

TABLE 57.2 Percentage of the Chemical Variables

Chemical variables	*Samples numbers*					
	1	2	3	4	5	6
Ca^{2+} (%)	41.68	27.04	11.08	16.10	15.97	14.98
Mg^{2+} (%)	29.45	44.58	15.98	23.22	22.37	17.96
Na^{+} (%)	28.56	26.82	70.25	57.89	59.86	64.34
K^{+} (%)	0.31	1.56	2.69	2.79	1.80	2.72
Total	100	100	100	100	100	100
HCO_3^- (%)	86.77	57.74	19.20	14.44	23.70	10.43
CO_3^{2-} (%)	–	5.64	–	–	–	–
Cl^- (%)	5.09	16.25	35.40	50.81	64.82	72.59
SO_4^{2-} (%)	5.76	16.92	42.39	19.81	8.43	13.70
NO_3^- (%)	1.74	2.84	2.79	14.71	2.85	3.14
F^- (%)	0.64	0.61	0.22	0.23	0.20	0.14
Total	100	100	100	100	100	100

TABLE 57.3 Hydrogeochemical Facies

Hydrogeochemical facies	*Sample numbers*	*Types*
$Ca^{2+} > Mg^{2+} > Na^{+} : HCO_3^- + SO_4^{2-} > Cl^-$	1	I
$Mg^{2+} > Ca^{2+} > Na^{+} : HCO_3^- + CO_3^{2-} > SO_4^{2-} > Cl^-$	2	I

$Na^+ > Mg^{2+} > Ca^{2+}$: $SO_4^{2-} > Cl^- > HCO_3^-$	3	II
$Na^+ > Mg^{2+} > Ca^{2+}$: $Cl^- > SO_4^{2-} > NO_3^- > HCO_3^-$	4	III
$Na^+ > Mg^{2+} > Ca^{2+}$: $Cl^- > SO_4^{2-} > HCO_3^-$	5	IV
$Na^+ > Mg^{2+} > Ca^{2+}$: $Cl^- > SO_4^{2-} > HCO_3^-$	6	IV

TABLE 57.4 Hydrogeochemical Facies in Relation to Residence Time of Water (Schoeller, 1967)

Residence time of water	*Types*	*Hydrogeochemical facies*	*Water type*	*Topography*
Initial stage (new and younger water)	I	$HCO_3^- + CO_3^{2-} > SO_4^{2-}$	Recharge	High
Duration of water stay increases	II	$SO_4^{2-} > Cl^-$	–	–
Still increasing duration of water stay	III	$Cl^- > SO_4^{2-} > NO_3^-$	–	–
Final stage (older water)	IV	$Cl^- > SO_4^{2-}$	Discharge	Low

As per the classification of facies with respect to residence time of water in aquifer material and topography (Tables 57.3 and 57.4), the groundwater samples 1 and 2 come under Type I (relating to recharge water), as they show $Ca^{2+} > Mg^{2+} > Na^+$: $HCO_3^- > SO_4^{2-} > Cl^-$ and $Mg^{2+} > Ca^{2+} > Na^+$: $HCO_3^- + CO_3^{2-} > SO_4^{2-} > Cl^-$ facies. The groundwater sample 3 is associated with Type II and the groundwater sample 4 comes under Type III due to progressive enrichment of ions and interference of anthropogenic activities on the groundwater system so that sample 4 shows NO_3^- enrichment (Table 57.1). The groundwater samples 5 and 6 are related to Type IV (relating to discharge water), as they show $Na^+ > Mg^{2+} > Ca^{2+}$: $Cl^- > SO_4^{2-} > HCO_3^-$. They also support the progressive enrichment of ions depending on residence time of water in the aquifer, the extent of water-rock interaction and anthropogenic sources.

Genetic classification of groundwater quality (Chebotarev, 1955): Groundwater quality is classified into major three types, as per its genetic classification (Table 57.5). They are

(i) HCO_3^- (ii) SO_4^{2-} and (iii) Cl^-. The groundwater samples 1 and 2 are observed from a major group of HCO_3^-, the groundwater samples 3 and 5 are observed from a major group of SO_4^{2-} and the groundwater samples 4 and 6 are observed from a major group of Cl^- (Table 57.6). The former type indicates intensive water flushing due to good drainage conditions, the latter type indicates inadequate water flushing due to quasi-stagnant conditions and the intermediate type signifies semi-water flushing between the former and the latter types. It suggests that the groundwater belonging to a major group of HCO_3^- comes under fresh water environment and is subsequently modified by the brackish type due to influence of anthropogenic activities on the groundwater system.

TABLE 57.5 Genetic Water Types (Chebotarev, 1955)

Major group	*Division*	*Genetic water type*	*Percent of ions*					
			$HCO_3^- + CO_3^{2-}$	Cl^-	SO_4^{2-}	$Cl^- + SO_4^{2-}$	$HCO_3^- + Cl^-$	$HCO_3^- + SO_4^{2-}$
HCO_3^-	I	HCO_3^-	> 40	–	–	< 40	–	–
	II	$HCO_3^- - Cl^-$	40 – 30	–	–	10 - 20	–	–
	III	$Cl^- - HCO_3^-$	30 – 15	–	–	20 - 35	–	–
SO_4^{2-}	IV	$SO_4^{2-} - Cl^-$	15 – 5	< 25	> 25	–	–	–
	V	SO_4^{2-}	–	–	> 40	–	> 10	–
Cl^-	III	$Cl^- - HCO_3^-$	30 – 15	> 20	–	–	–	–
	IV	$Cl^- - HCO_3^-$	15 – 5	> 20	–	–	–	< 25
	V	Cl^-	< 5	> 40	–	–	–	–

TABLE 57.6 Genetic Classification of Groundwater Quality

Major group	*Division*	*Genetic type*	*Sample numbers*
HCO_3^-	I	HCO_3^-	1 and 2
SO_4^{2-}	III	$Cl^- - HCO_3^-$	3 and 5
Cl^-	IV	$Cl^- - HCO_3^-$	4 and 6

(b) Evaluation of groundwater quality

Piper's diagram (1944): A trilinear diagram is an effective tool for segregating data for critical study with respect to the sources of dissolved ions in water and modifications in water character (Piper, 1944). The diagram has two triangular fields relating to cations (Ca^{2+}, Mg^{2+} and $Na^+ + K^+$) on left hand side and anions (HCO_3^-, CO_3^{2-}, Cl^- and SO_4^{2-}) on right-hand side, and a diamond-shaped field on upper side relating to all ions (Figure 57.1), which represents an overall geochemical character of water quality in terms of nine zones (below). Each triangular field and diamond shaped field are divided into five parts, separating by 20%, after converting the ions from mg/l into meq/l.

The percentages of Ca^{2+}, Mg^{2+}, Na^{+}+K^{+}, $HCO_3^- + CO_3^{2-}$, Cl^- and SO_4^{2-} vary from 11.08 to 41.68, 15.98 to 44.58, 27.38 to 72.94, 10.43 to 86.77, 5.09 to 72.59 and 5.76 to 42.39, respectively (Table 57.2). The groundwater samples 1 and 2 are observed from zone 5, which comes under carbonate hardness or fresh water type (Figure 57.1 and Table 57.7). They are characterised by Ca^{2+} and Mg^{2+} of HCO_3^- and CO_3^{2-} over Na^+ and K^+ of Cl^- and SO_4^{2-}. Whereas, the groundwater samples 3 to 6 fall in zone 7, which shows non-carbonate alkali. They belong to brackish or saline water, which is characterised by Na^+ and K^+ of Cl^- and SO_4^{2-} over Ca^{2+} and Mg^{2+} of HCO_3^- and CO_3^{2-}. It suggests that the fresh groundwater quality has become brackish due to influence of anthropogenic activities on the groundwater system.

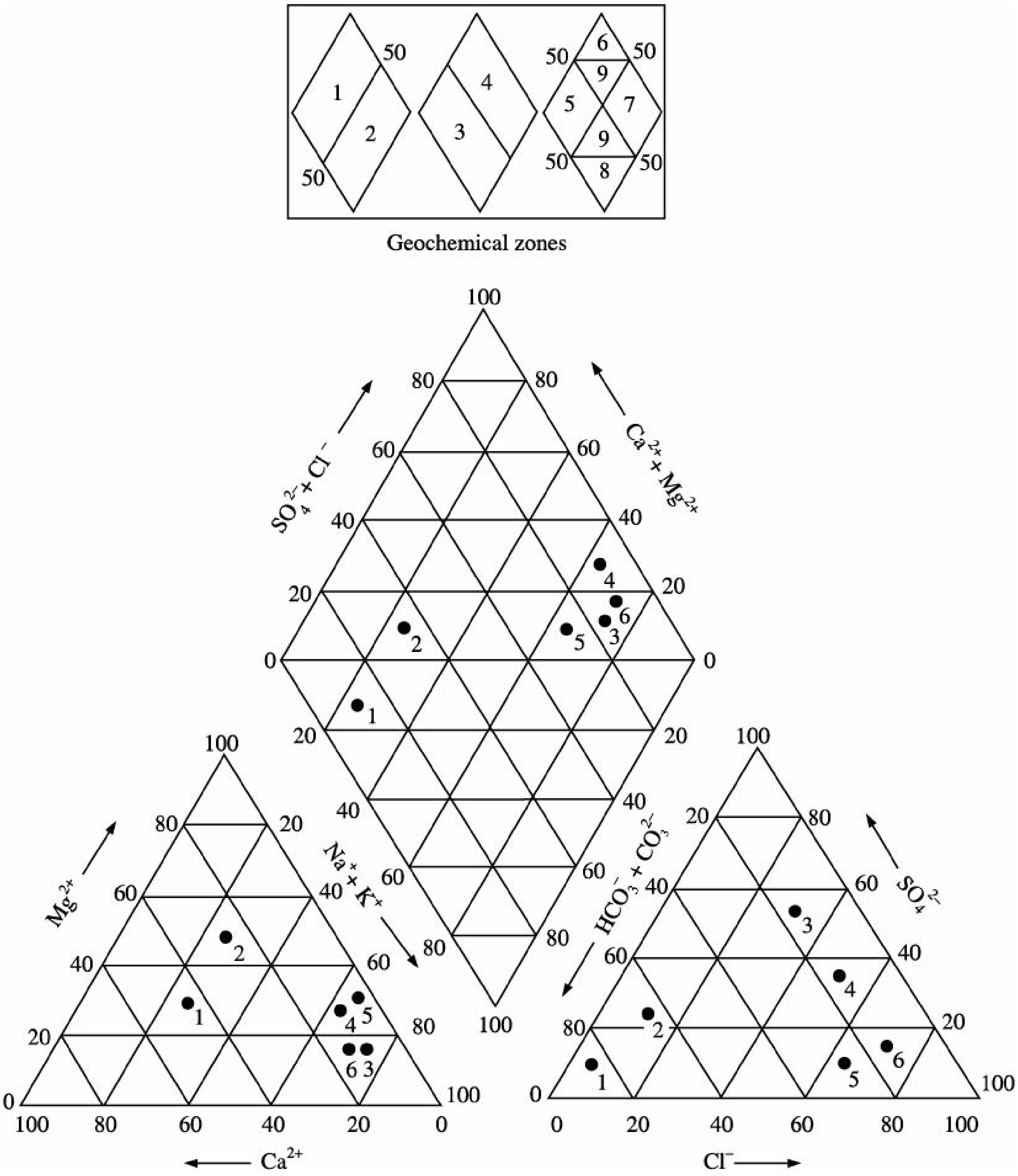


FIGURE 57.1 Piper's trilinear diagram.

TABLE 57.7 Characterisation of Water Quality Following Trilinear Diagram

Zone	*Characterisation of water quality*	*Sample numbers*
1	Alkaline earths (Ca^{2+} + Mg^{2+}) exceed alkalies (Na^+ + K^+)	1 and 2
2	Alkalies exceed alkaline earths	3 to 6
3		1 and 2

	Weak acids HCO_3^- + CO_3^{2-} exceed strong acid Cl^- + SO_4^{2-}	
4	Strong acids exceed weak acids	3 to 6
5	Carbonate hardness (secondary alkalinity) exceeds 50% that is by alkaline earths and weak acids	1 and 2
6	Non-carbonate hardness (secondary salinity) exceeds 50%	–
7	Non-carbonate alkali (primary salinity) exceeds 50%	3 to 6
8	Carbonate alkali (primary alkalinity) exceeds 50%	–
9	Mixed type (transition zone)—No cation-anion pair exceeds 50%	–

(c) Mechanisms controlling groundwater quality

Gibbs's diagrams (1970): Gibbs (1970) proposed two diagrams—one is related to the ratio of cations ($Na^+ + K^+ : Na^+ + K^+ + Ca^{2+}$) and another is associated with the ratio of anions ($Cl^- : Cl^- + HCO_3^-$), which are plotted against the TDS, for understanding the mechanisms that control the groundwater chemistry with respect to atmospheric precipitation (rainfall), rock-water interaction and evaporation (Figure 57.2).

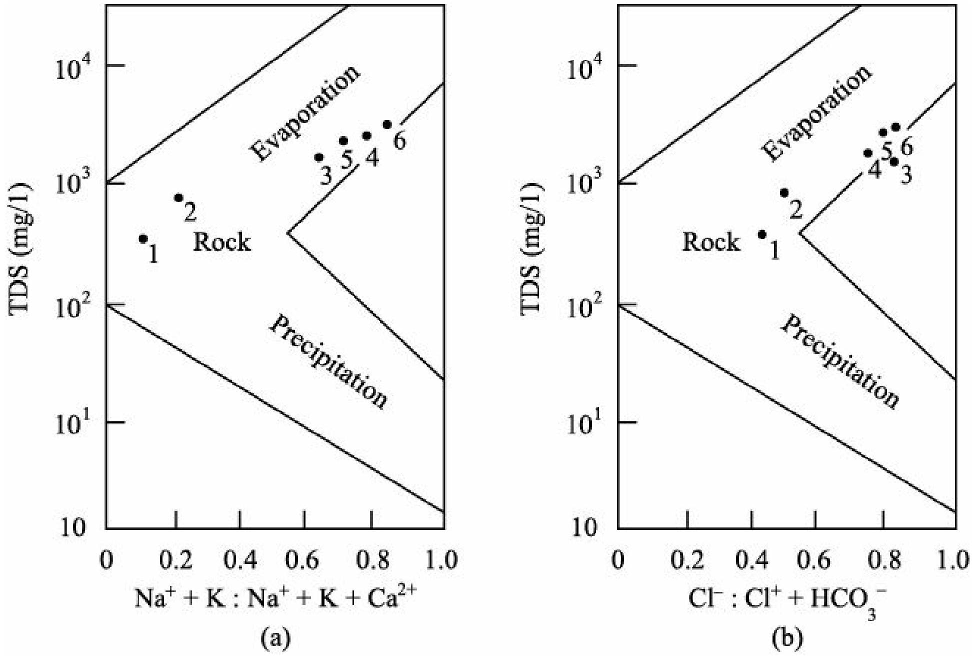


FIGURE 57.2 Mechanisms controlling groundwater chemistry.

If the value of TDS is less than 100 mg/l, with a dominance of Ca^{2+} and HCO_3^- over Na^+ and Cl^-, the chemistry of water falls in the precipitation domain, indicating a meteoric origin. The soil and/or rock-water interaction is responsible for the source of dissolved ions over the control of water chemistry, with a progressive increase in Na^+ and $Cl^–$ ions over Ca^{2+} and HCO_3^-, so that the value of TDS varies from 100 mg/l to 1,000 mg/l. If the water is influenced by dry climate or marine environment or anthropogenic activity, the water quality could be changed as brackish or saline due to abundance of Na^+ and $Cl^–$ over Ca^{2+} and HCO_3^-, with the consequent higher TDS (>1,000 mg/l). Thus, such chemistry falls in the evaporation domain.

The ratio of cations (Na^+ + K : Na^+ + Ca^{2+}) varies from 0.41 (sample 1) to 0.86 (sample 3) and that of anions ($Cl^–$: $Cl^–$ + HCO_3^-) from 0.10 (sample 1) to 0.87 (sample 6; Table 57.8). They are plotted against the TDS, which explain the groundwater quality with respect to precipitation, rock-water interaction and evaporation (Figure 57.2). The groundwater samples 1 and 2 are observed from the rock domain, where the value of TDS is less than 1,000 mg/l, while the groundwater samples 3 to 6 are observed from the domain of evaporation, where the value of TDS is more than 1,000 mg/l.

TABLE 57.8 Ratios of Cations and Anions

Sample Number	*TDS*	Na^+ : Na^+ + Ca^{2+}	$Cl^–$: $Cl^–$ + HCO_3^-
1	545	0.41	0.10
2	960	0.50	0.20
3	1,170	0.86	0.65
4	1,630	0.78	0.78
5	2,030	0.79	0.73
6	2,390	0.81	0.87

The geogenic origin (rock-water interaction) appears as a result of dissolved ions in the groundwater samples 1 and 2, and hence, the value of their TDS is less than 1,000 mg/l (fresh water; Figure 57.2). Whereas, the anthropogenic activities increase the concentrations of Na^+ and $Cl^–$, and consequently, make the value of TDS higher, which is more than 1,000 mg/l (brackish water). As a result, the groundwater samples move from the domain of rock towards the domain of evaporation. Thus, it suggests that the original quality of fresh groundwater developed by geogenic origin is subsequently modified to brackish due to interferences of anthropogenic sources.

Langelier and Ludwig's diagram (1942): The evolution of groundwater quality is represented in Langelier and Ludwig's graphical diagram (Figure

57.3). The groundwater samples 1 and 2 fall in Group I, relating to Ca^{2+} – Mg^{2+} – HCO_3^- type, which indicates a meteoric origin of water quality. This is caused by rock-water interaction. The rest of the groundwater samples 3 to 6 are observed in Group II, where the groundwater quality is dominated by Na^+ + K^+ and Cl^- + SO_4^{2-} over Ca^{2+} + Mg^{2+} and $HCO_3^- + CO_3^{2-}$. The HCO_3^- and Cl^- distinguish the fresh and brackish water environments, respectively. The groundwater quality in Group II is caused by anthropogenic activities (drainage waste, agricultural fertilisers, industrial effluents, etc.). Thus, the evolution of the chemical characteristics of the groundwater in Group I and Group II infers that the chemistry of groundwater is mainly controlled by geogenic process in the former group, which is subsequently modified by the anthropogenic sources in the latter group.

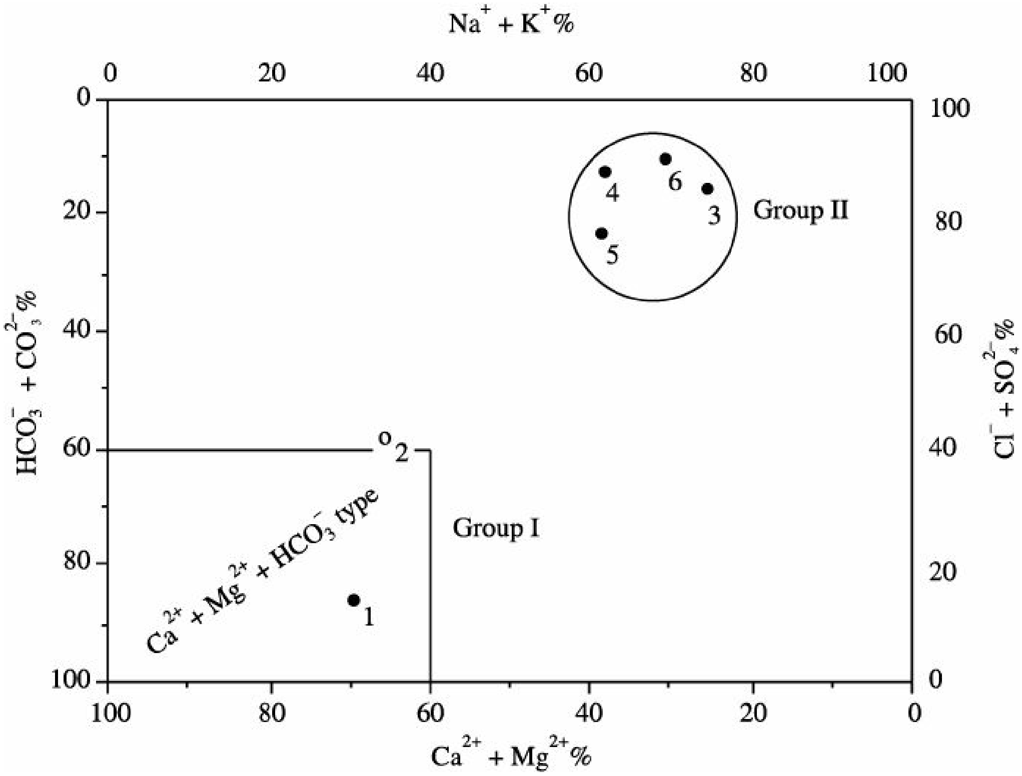


FIGURE 57.3 Evolution of groundwater quality.

(d) Geochemical signatures: The geochemical signatures (ratios) are widely used to assess the origin of water (Table 57.9). For example, HCO_3^- is a dominant ion in groundwater, while Cl^- is an abundant ion in seawater. Therefore, if the ratio HCO_3^- : Cl^- is more than unity (3.90 and 17.05 in the samples 2 and 1, respectively; Table 57.10), then it indicates that the non-marine origin of water is caused by interaction of water with the aquifer materials. This is related to recharge water. On the other hand, if the ratio $Na^+ : Cl^-$ is less than unity (0.88 and 0.93 in the samples 6 and 5, respectively), it indicates the marine or anthropogenic origin. The higher of this (1.11 to 5.83 in the samples 1 to 4) indicates that the water is flowing through the crystalline rocks. This is associated with the discharge water. Similarly, the ratio $Mg^{2+} : Ca^{2+}$ is more than one (1.20 to 1.65 in the samples 2 to 6), reflecting either enrichment of ferromagnesium minerals, anthropogenic pollution or seawater. The higher ratio of $Na^+ : K^+$ (17.21 to 92.04 in the samples from 1 to 6) suggests the influence of rocks. The higher values of $Ca^{2+}+Mg^{2+}/Na^++K^+$

(2.46 to 2.52) are observed from the samples 1 and 2 compared to those from the samples 3 to 6

(0.37 to 0.65). The former indicates an exchange of Na^+ and K^+ against Ca^{2+} or Mg^{2+}, while the latter indicates the deficiency of Na^+ and K^+ against Ca^{2+} or Mg^{2+}. The ratio $Na^+ : Ca^{2+}$ shows less than unity (0.69 and 0.99) in the samples 1 and 2, indicating reverse exchange, and more than unity (3.60 to 6.34) in the samples 3 to 6, indicating base exchange. All water samples show the ratio $Ca^{2+} : SO_4^{2-} + HCO_3^-$ is less than unity (0.18 to 0.67), suggesting the flow of water through the normal hydrological cycle.

TABLE 57.9 Geochemical Signatures (GS)

GS	*Range*	*Influence of*
$HCO_3^- : Cl^-$	> 1.0	Organic matter and/or CO_2 or recharge area or upper water flow course of carbonate rocks
	< 1.0	Lower water flow course of carbonate rocks
	< 0.2	Saline water and brines
$Na^+ : Cl^-$	0.876	Seawater
	< 0.876	Replacement of Na^+ by Ca^{2+} or Mg^{2+}
	< 0.7	Loss of Na^+ through precipitation of evaporite rocks
	> 1.0	Water flow through crystalline or volcanic rocks
$Mg^{2+} : Ca^{2+}$	0.5 to 0.7	$CaCO_3$ rocks
	0.7 to 0.9	$CaMg(CO_3)_2$ rocks

	> 0.9	Mg^{2+} rich rocks or seawater mixture
	< 0.5	Ca^{2+} rich water
$Na^+ : K^+$	15 to 25	Natural recharge area
	50 to 70	Lower water flow course
	> 70	Volcanic rocks
	< 15	Na^+ depleted water
$Ca^{2+} + Mg^{2+} : Na^+ + K^+$	> 1.0	Upper water flow course of carbonate rocks or precipitation of NaCl from brine or exchange of Na^+ and K^+ against Ca^{2+} and/or Mg^{2+}
	< 1.0	Lower water flow course of carbonate rocks
$Na^+ : Ca^{2+}$	> 1.0	Base ion exchange
	< 1.0	Reverse ion exchange
$Ca^{2+} : SO_4^{2-} + HCO_3^-$	< 1.0	Normal hydrological cycle
	> 1.0	$Ca^{2+} – Cl^-$ brines

TABLE 57.10 Geochemical Signatures (GS)

GS	*Sample numbers*					
	1	2	3	4	5	6
$HCO_3^- : Cl^-$	17.05	3.90	0.54	0.28	0.37	0.14
$Mg^{2+} : Ca^{2+}$	0.99	1.65	1.44	1.44	1.40	1.20
$Na^+ : Cl^-$	5.83	1.65	1.99	1.11	0.93	0.88
$Na^+ : K^+$	92.04	17.21	26.05	20.80	33.22	24.13
$Ca^{2+} + Mg^{2+} : Na^+ + K^+$	2.46	2.52	0.37	0.65	0.62	0.49
$Na^+ : Ca^{2+}$	0.69	0.99	6.34	3.60	3.75	4.30
$Ca^{2+} : SO_4^{2-} + HCO_3^-$	0.45	0.34	0.18	0.46	0.50	0.67

Chloro-alkaline indices (Schoeller, 1965, 1977): Changes in chemical composition of groundwater along its flow path can be understood by studying the chloro-alkaline indices (CA). Schoeller (1965, 1977) suggested two chloro-alkaline indices (CA1, CA2) for the interpretation of ion exchange between groundwater and host environment. A positive CA index indicates the exchange of Na^+ and K^+ from the water with Mg^{2+} and Ca^{2+} of the rocks, and is negative, when there is an exchange of Mg^{2+} and Ca^{2+} of the water with Na^+ and K^+ of the rocks.

The chloro-alkaline (CA) indices are computed using Eqs. (57.1) and

(57.2).

$$CA1 = [Cl^- - Na^+ + K^+ : (Cl^-)] \tag{57.1}$$

$$CA2 = [Cl^- - Na^+ + K^+ : (SO_4^{2-} + HCO_3^- + NO_3^-)] \tag{57.2}$$

TABLE 57.11 Chloro-alkaline Indices

CA indices	*Sample numbers*					
	1	2	3	4	5	6
CA1	–4.72	–0.75	–1.07	–0.16	0.05	0.08
CA2	–0.26	–0.16	–0.59	–0.16	0.09	0.22

The groundwater samples 1 to 4 show negative CA1 (–0.16 to –4.72) and CA2 (–0.16 to –0.59; Table 57.11), confirming cation–anion exchange reaction, in which ion exchange takes place between Ca^{2+} and Mg^{2+} in the groundwater and Na^+ and K^+ in the aquifer material. This, further, confirms that the host rocks are the primary sources of dissolved ions in the groundwater, in which the ion exchange is one of the major contributors for higher concentration of Na^+ and K^+ in the groundwater. The rest of the groundwater samples 5 and 6 have positive CA1 (0.05 to 0.08) and CA2 (0.09 to 0.22), confirming a base exchange reaction, where exchange occurs between Na^+ and K^+ in the groundwater, and Ca^{2+} and Mg^{2+} in the aquifer material.

PROBLEM 58 From Table 58.1, justify the suitability of quality of groundwater for
(a) drinking, (b) irrigation, and (c) industrial purposes.

Key Concept Assessment of groundwater quality is essential with respect to drinking, irrigation and industrial purposes on the basis of set of a criteria or standards of acceptable quality for that use. If the water is in poor quality, it does not favour for any developmental activities.

Data of the given problem

TABLE 58.1 Suitability of Water Quality for Drinking Purpose (BIS, 2012)

Chemical variables	*HDL*	*MPL*	*Samples numbers*					
			1	2	3	4	5	6

Temperature	–	–	21	20	23	23	24	26
Colour (HU)	5	15	2	2	3	6	7	7
Odour	Agreeable		Agreeable			Objectionable		
Taste	Agreeable		Agreeable			Objectionable		
Turbidity (JTH)	1	5	1	1	2	6	6	9
pH	6.5 to 8.5	6.5 to 9.2	8.2	8.3	7.3	8.0	7.8	6.8
TDS (mg/l)	500	2,000	**545**	**960**	**1,170**	**1,630**	**2,030**	**2,390**
TH (mg/l)	200	600	**298**	**529**	**244**	**488**	**595**	**604**
TA (mg/l)	200	600	**361**	**468**	172	185	369	193
Ca^{2+} (mg/l)	75	200	70	**80**	40	**80**	**100**	**110**
Mg^{2+} (mg/l)	30	100	30	**80**	**35**	**70**	**85**	**80**
Na^+ (mg/l)	200	–	55	91	**291**	**330**	**430**	**542**
Cl^- (mg/l)	250	1,000	15	85	225	**460**	**715**	**950**
SO_4^{2-} (mg/l)	200	400	23	120	**365**	**243**	126	**243**
NO_3^- (mg/l)	45	–	9	26	31	**233**	**55**	**72**
F^- (mg/l)	1.0	1.5	1.0	**1.7**	0.8	1.1	1.2	0.9

Solution

(a) Drinking purpose: A quality criterion is generally based on water intake per person per day. Drinking water should be free from the pollution. If it is contaminated, the water should be treated before its consumption. The highest desirable limits (HDLs) should be given to the top priority prescribed for drinking purpose, while the maximum permissible limits (MPLs) may be extended, if there is no water availability.

The concentrations of TDS (545 mg/l) and TA (361 mg/l) are more than the highest desirable limits (500 and 200 mg/l) in the groundwater sample 1 prescribed for drinking (Table 58.1). Whereas, the water quality in samples 2 to 6 comes under non-potable category, as the recommended standards exceed their limits for drinking. Thus, they cause health disorders.

(b) Irrigation purpose: Excessive concentrations of dissolved ions in the irrigation water affect plants and agricultural soil physically and chemically through lowering of osmotic pressure in the plant structural cells. This prevents water from reaching the branches and leaves, thus reducing the agricultural productivity. Salinity hazard, sodium hazard, percent sodium (%Na^+), permeability index (PI), residual sodium carbonate (RSC), magnesium ratio (MR) and Kelly ratio (KR) are widely used for the assessment of water quality for irrigation.

Salinity hazard and sodium hazard: Salinity hazard (*C*) causes poor drainage conditions. Sodium hazard (*S*) makes soil compact and impervious, and hence, it reduces plant growth. The former hazard is expressed in terms of EC. The latter hazard is computed in terms of sodium adsorption ratio (SAR) as well as in terms of percent sodium (%Na^+), where the ions are expressed in meq/l.

The SAR is the ratio of sodium to square root product of calcium and magnesium (Eq. 58.1).

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \tag{58.1}$$

The %Na^+ is the ratio of alkalis (sodium and potassium) to alkaline earths (calcium and magnesium) and alkalies (Eq. 58.2), which is expressed in percentage (%).

$$\%Na^+ = \left[\frac{(Na^+ + K^+)}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)}\right] \times 100 \tag{58.2}$$

TABLE 58.2 Values of SAR, %Na^+, PI, RSC, MR and KR

Chemical parameter	*Groundwater samples*					
	1	2	3	4	5	6
EC (μS/cm)	840	1,500	1,800	2,500	3,120	3,680
SAR	1.39	1.72	8.11	6.50	7.64	9.60
%Na^+	28.87	28.32	72.95	60.68	61.66	67.06
PI	60.80	53.06	79.58	67.52	69.80	71.65
RSC	1.25	–1.22	–1.43	–6.06	–4.61	–8.22
MR	41.40	62.24	59.06	59.06	58.35	54.52
KR	0.40	0.37	2.60	1.47	1.56	1.95

USSLS's diagram (1954): The United States Soil Laboratory Staff's (USSLS's) diagram classifies the water quality into 16 zones to assess the degree of suitability of water for irrigation (Figure 58.1), in which the salinity hazard (*C*) can be divided into four sub-zones, viz. low salinity hazard (*C*1, <250 µS/cm), medium salinity hazard (*C*2, 250 to 750 µS/cm), high salinity hazard (*C*3, 750 to 2,250 µS/cm), and very high salinity hazard (*C*4, >2,250 µS/cm), considering them as good, moderate, poor and very poor water classes, respectively. Similarly, the sodium hazard (*S*) can also be classified into four sub-zones, viz. low sodium hazard (*S*1, <10), medium sodium hazard (*S*2, 10 to 18), high sodium hazard (*S*3, 18 to 26), and very high sodium hazard (*S*4, >26), considering them as good, moderate, poor, and very poor classes, respectively.

The values of EC vary from 840 µS/cm (sample 1) to 3,680 µS/cm (sample 6) and those of SAR vary from 1.39 (sample 1) to 9.60 (sample 6), respectively (Table 58.2). A combined effect of EC and SAR on plant growth is shown in a diagram of United States Salinity Laboratory (Figure 58.1). The groundwater samples 1 and 2 are observed from the *C*3*S*1 zone, sample 3 from *C*3*S*2 zone, samples 4 and 5 from *C*4*S*2 zone and sample 6 from *C*4*S*3 zone, indicating an increase in salinity hazard and sodium hazard for irrigation. Thus, the salt-crops tolerant can be selected, following the special treatment methods to the soils.

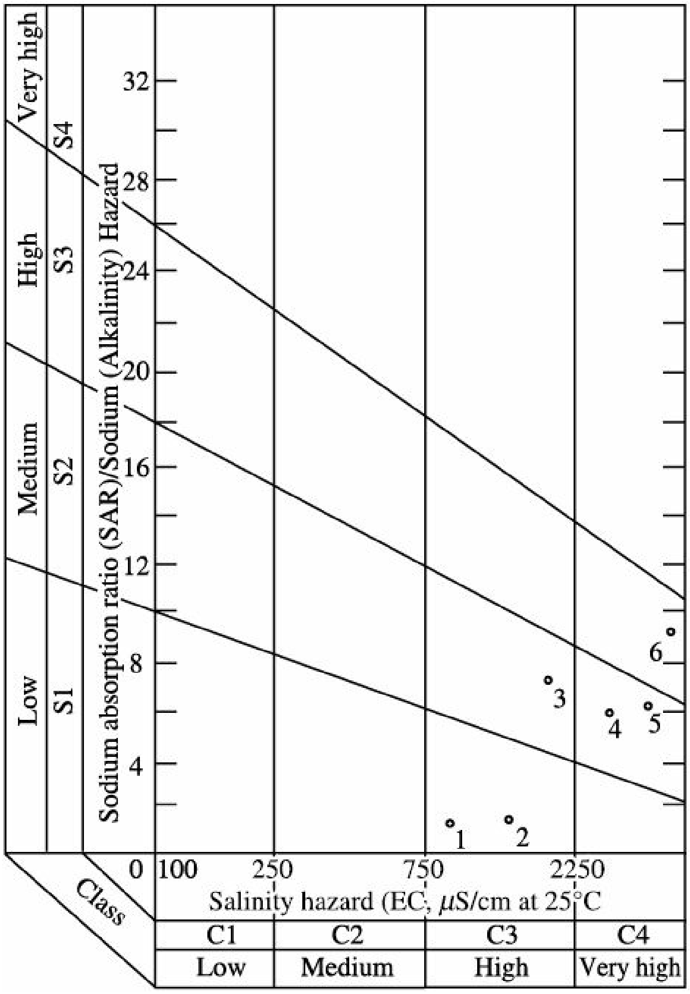


FIGURE 58.1 USSLS's (1954) classification of groundwater quality for irrigation.

Per cent sodium: If percent Na^+ increases, it reduces the permeability of soils. Thus, the soils require special treatment like gypsum to increase their permeability for crop growth. The $\%Na^+$ can be computed as shown in Eq. (58.2), following the concentrations of ions in meq/l.

The $\%Na^+$ can be classified for irrigation water quality as shown below:

TABLE 58.3 Classification of $\%Na^+$ for Irrigation

$\%Na^+$ range	*Suitability*	*Sample numbers*
< 60	Suitable	1 and 2
> 60	Unsuitable	3 to 6

As per the $\%Na^+$, the groundwater samples 1 and 2 show $\%Na^+$ less than 60 (28.32 to 28.87) and the rest 3 to 6 show $\%Na^+$ more than 60 (60.68 to 72.95; Tables 58.2 and 58.3). Therefore, the quality of groundwater in the former samples is suitable and in the latter samples is not suitable.

Wilcox's diagram (1955): For judging the suitability of water quality for irrigation, Wilcox proposed a diagram with respect to a combination of EC and %Na^+. This combination classifies the diagram into five zones of excellent to good, good to permissible, permissible to doubtful, doubtful to unsuitable and unsuitable, with increasing salinity hazard and sodium hazard for irrigation (Figure 58.2).

The EC varies from 840 μS/cm to 3,680 μS/cm and %Na^+ varies from 28.32 (sample 2) to 72.95 (sample 3), respectively (Table 58.2). The groundwater samples 1 and 2 fall in the good to permissible zone, sample 3 in the permissible to doubtful zone and sample 4 in the doubtful to unsuitable zone and, samples 5 and 6 in the unsuitable zone for irrigation so that the crops of salt tolerance can be selected by giving special treatment to soils.

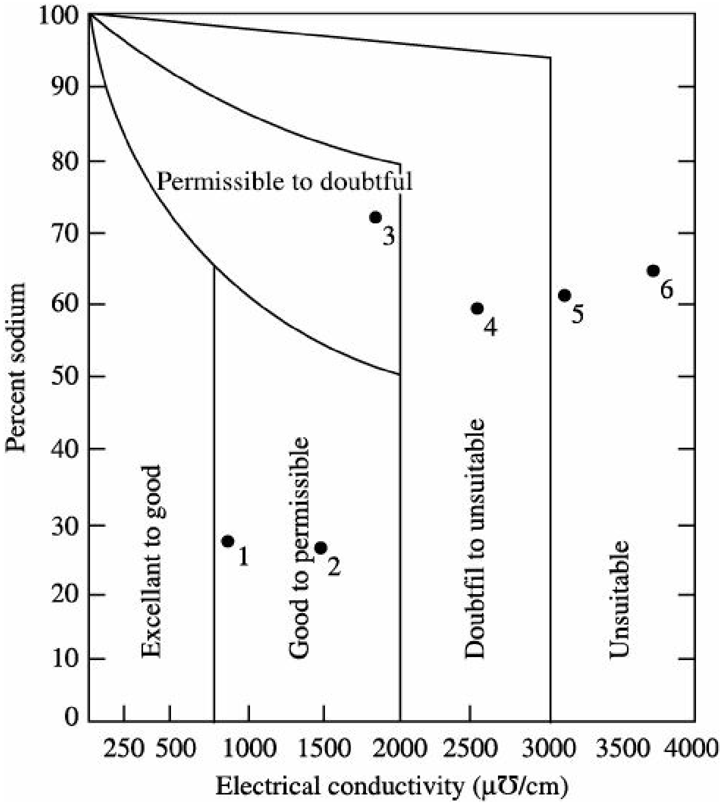


FIGURE 58.2 Wilcox's (1954) classification of groundwater quality for irrigation.

Permeability index (Doneen, 1964): Permeability is greatly influenced by Na^+, Ca^{2+}, Mg^{2+}, HCO_3^- and Cl^- contents of soil, and hence, is affected by long-term use of irrigation water, with high salt content. It plays a vital role in the growth of plants. If the permeability is low in the soil zone, it does not support plant growth. The degree of permeability condition in the soil is expressed in terms of permeability index (PI) and can be computed as shown below (Eq. 58.3). The concentrations of ions are expressed in meq/l.

The *PI* is the ratio of sodium and square root of the bicarbonate to calcium, magnesium and sodium, which is expressed in percentage (%).

$$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{(Ca^{2+} + Mg^{2+} + Na^{+})} \times 100 \tag{58.3}$$

The *PI* varies from 53.06 (sample 2) to 79.58 (sample 3; Table 58.2). According to the classification of PI (Table 58.4), the groundwater sample 3 comes under the suitable category and the rest 1 and 4 to 6 come under the marginally suitable category for irrigation due to decrease in permeability.

TABLE 58.4 Classification of PI for Irrigation

Classification of PI	*Maximum permeability*	*Suitability*	*Sample numbers*
I	75% to 100%	Suitable	3
II	25% to 75%	Marginal	1 and 4 to 6
III	< 25%	Unsuitable	–

With relation of PI to the total concentration (Figure 58.3), the groundwater sample 1 falls in Class II (75% maximum permeability) and samples 2 to 6 fall in Class I (100% permeability) for irrigation.

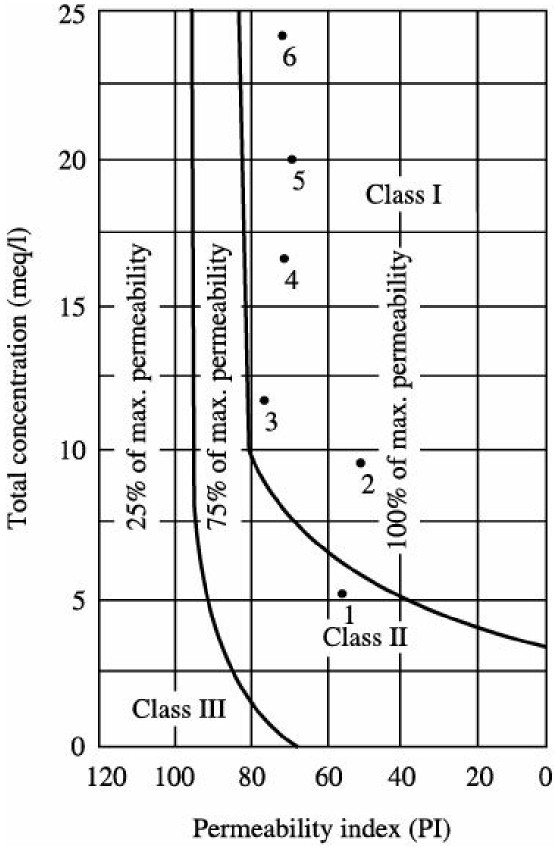


FIGURE 58.3 Doneen's permeability index (1964) chart for classification of water quality for irrigation.

Residual sodium carbonate (Richards, 1954): Carbonates $(HCO_3^- + CO_3^{2-})$ have an effect on water quality through precipitation of alkaline earths (Ca^{2+} + Mg^{2+}), thereby increasing the percentage of Na^+. This is more when the concentration of carbonates is in excess than that of alkaline earths. The excess carbonates combine with Na^+ to form $NaHCO_3$, which affects soil structure. This is called *residual sodium carbonate* (*RSC*). The higher RSC leads to an increase of adsorption of Na^+ in soil, which reduces soil permeability, and hence, does not support plant growth.

The *RSC* is the difference between carbonates $(HCO_3^- + CO_3^{2-})$ and alkaline earths
(Ca^{2+} + Mg^{2+}), which is expressed in milliequivalent per litre (meq/l).

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \tag{58.4}$$

The values of *RSC* is from –1.22 (sample 2) to 1.25 (sample 1; Table 58.2).

As per the classification of the *RSC* (Table 58.5), the groundwater samples 1 to 6 come under suitable type for irrigation, as the lower RSC does not increase the adsorption of Na^+ in soil. Thus, it does not reduce the soil permeability, as in the case of higher RSC.

TABLE 58.5 Classification of RSC for Irrigation

RSC Range (meq/l)	*Suitability*	*Sample numbers*
< 1.25	Suitable	1 to 6
1.25 to 2.50	Marginal	–
>2.50	Unsuitable	–

Magnesium ratio (Szaboles and Darab, 1964): Generally, Ca^{2+} and Mg^{2+} maintain a state of equilibrium in water. They do not behave equally in soil system. Magnesium damages soil structure, when water possesses more Na^+ and high salinity. Normally, a high level of Mg^{2+} is caused by exchangeable Na^+ in irrigated soils. In equilibrium, more Mg^{2+} can affect soil quality by rendering it alkaline. Thus, it affects crop yields. The adverse condition of magnesium on crop yields is expressed in terms of *magnesium ratio* (*MR*). This is defined as the ratio of magnesium to alkaline earths (Ca^{2+} + Mg^{2+}), and is expressed in percentage (%). It is computed as follows:

$$MR = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \tag{58.5}$$

The value of MR is in between 41.40 (sample 1) and 62.24 (sample 2; Table 58.2). The groundwater quality in sample 1 is suitable and in the rest samples 2 to 6, it is unsuitable for irrigation (Table 58.6), as magnesium damages the soil structure, which affects the crop yields.

TABLE 58.6 Classification of MR for Irrigation

MR	*Suitability*	*Sample numbers*
< 50	Suitable	1
> 50	Unsuitable	2 to 6

Kelly's ratio (Kelley, 1963): Kelly's ratio (KR) is used to classify the irrigation water quality, which is the level of Na^+ measured against Ca^{2+} and Mg^{2+}. The formula for calculating the KR is given in Eq. 58.6, where the concentrations of ions are in meq/l. If the KR is less than one, it is suitable for irrigation, and if it is more than one, it is unsuitable for irrigation.

The KR is the ratio of sodium to alkaline earths (Ca^{2+} + Mg^{2+}), which is expressed in percentage (%).

$$KR = \frac{Na^{+}}{(Ca^{2+} + Mg^{2+})} \tag{58.6}$$

The value of KR varies from 0.37 (sample 2) to 2.60 (sample 3; Table 58.2). According to the classification of KR (Table 58.7), the groundwater samples 1 and 2 are suitable for irrigation and the rest of the samples (3 to 6) are not suitable for irrigation due to increase in Na^{+} against Ca^{2+} and Mg^{2+}, which reduces the soil permeability.

TABLE 58.7 Classification of KR for Irrigation

KR	*Suitability*	*Sample numbers*
<1.0	Good	1 and 2
>1.0	Not good	3 to 6

(c) Industrial purpose: Utilisation of water for industry is quite diverse and water quality requirements vary greatly for different industries and even for different plants within the same industry. Every industry has its own standards for assessing the water quality. However, industrial sectors frequently suffer from incrustation and corrosion activities due to inferior water quality. The *incrustation* involves a deposition of undesired material of $CaCO_3$ on metal surfaces, while *corrosion* is a chemical action on metals, which results in metals being eaten away. Therefore, the following generalised water quality criterion has been adopted for deciding the incrusting and corrosive properties of water (Table 58.8).

TABLE 58.8 Water Quality Criteria for Industry

Chemical variable	*Criteria*	*Incrustation*	*Sample numbers*	*Corrosion*	*Sample numbers*
pH	< 7	–		P	–
TDS (mg/l)	> 1,000	–		P	3 to 6
TH (mg/l)	> 300	P	2 and 4 to 6	–	
HCO_3^{-} (mg/l)	> 400	P	1, 2 and 5	–	
Cl^{-} (mg/L)	> 500	–		P	5 and 6
SO_4^{2-} (mg/L)	> 100	P	2 to 6	–	

As per the water quality criteria for industrial purpose (Table 58.8), the groundwater quality develops incrustation in samples 2 and 4 to 6 due to high

TH, in samples 1, 2 and 5 due to high HCO_3^-, and also in samples 2 to 6 due to high SO_4^{2-}. Corrosion can be developed in water samples 3 to 6 due to high TDS, and in water samples 5 and 6 due to high Cl^-.

Langelier Index (Langelier, 1936): Langelier index (LI) is also called *$CaCO_3$ saturation index*.

This is an indication of instability with respect to $CaCO_3$ and it determines the corrosive or incrusting ability of water. It is defined as the difference between the measured pH and the calculated pH.

$$LI = \text{pH} - \text{pH}_s \tag{58.7}$$

where,

LI = langelier index

pH = actual pH of water (measured pH in the field)

pH_s = saturation pH or calculated pH at which, without change in total alkalinity and calcium content, water would be in equilibrium with solid $CaCO_3$

The pH_s can also be defined as the difference between the total TDS and water temperature, and the total TH and alkalinity.

$$\text{pH}_s = 9.3 + (A + B) - (C + D) \tag{58.8}$$

where,

A = factor of TDS

B = factor of water temperature

C = $CaCO_3$ content in mg/l or 2/3rd of the TH (mg/l)

D = methyl orange alkalinity expressed as $CaCO_3$ (mg/l)

A zero value of LI indicates a chemical balance in water. A positive value of LI indicates a tendency to deposit $CaCO_3$ and a negative value of LI shows a tendency to dissolve $CaCO_3$.

The computed values of the LI for the chemical analysis of groundwater (Table 58.2) are presented in Table 58.9, following the procedure as shown in Table 58.10.

TABLE 58.9 Values of Langelier Index

S. No.	*A*	*B*	*C*	*D*	*pH*	pH_s	*LI*	*Affected by*
1	0.2	2.0	1.9	2.6	8.2	7.0	1.2	Incrustation
2	0.2	2.0	2.2	2.7	8.3	6.6	0.7	Incrustation
3	0.2	2.0	1.8	2.2	7.3	7.5	–0.2	Corrosion
4	0.2	2.0	2.1	2.3	8.0	7.1	0.9	Incrustation
5	0.2	2.0	2.2	2.6	7.8	6.7	1.1	Incrustation
6	0.2	2.0	2.2	2.3	6.8	7.0	–0.2	Corrosive

The groundwater occurring in samples 1, 2, 4 and 5 can develop incrustation, that in samples 3 and 6 can develop corrosion.

TABLE 58.10 Langelier Coefficients

TDS (mg/l)	*A*	*Temperature* (^{o}C)	*B*	*Calcium hardness or* 2/3rd *total hardness* (*as* $CaCO_3$)	*C*	*Total alkalinity* (*as* $CaCO_3$)	*D*
50 to 300	0.1	–	–	10 to 11	0.6	10 to 11	1.0
400 to 1,000	0.2	–	–	12 to 13	0.7	12 to 13	1.1
–	–	–	–	14 to 17	0.8	14 to 17	1.2
–	–	–	–	18 to 22	0.9	18 to 22	1.3
–	–	–	–	23 to 27	1.0	23 to 27	1.4
–	–	–	–	28 to 34	1.1	28 to 35	1.5
–	–	0 to 1	2.6	35 to 43	1.2	36 to 44	1.6
–	–	2 to 6	2.5	44 to 55	1.3	45 to 55	1.7
–	–	7 to 9	2.4	56 to 69	1.4	56 to 69	1.8
–	–	10 to 13	2.3	70 to 87	1.5	70 to 88	1.9
–	–	14 to 17	2.2	88 to 110	1.6	89 to 110	2.0
–	–	18 to 21	2.1	111 to 138	1.7	111 to 139	2.1
–	–	22 to 27	2.0	139 to 174	1.8	140 to 176	2.2
–	–	28 to 31	1.9	175 to 220	1.9	177 to 220	2.3
–	–	32 to 37	1.8	230 to 270	2.0	230 to 270	2.4
–	–	38 to 43	1.7	280 to 340	2.1	280 to 350	2.5
–	–	44 to 50	1.6	350 to 430	2.2	360 to 440	2.6
–	–	51 to 56	1.5	440 to 550	2.3	450 to 550	2.7
–	–	57 to 63	1.4	560 to 690	2.4	560 to 690	2.8
–	–	64 to 71	1.3	700 to 870	2.5	700 to 880	2.9
		72 to 81	1.2	880 to 1,000	2.6	890 to 1,000	3.0

Note: *A* = Factor of TDS; *B* = factor of water temperature; *C* = $CaCO_3$ content in mg/l or 2/3rd of the TH (mg/l) and *D* = methyl orange alkalinity expressed as $CaCO_3$ (mg/l).

PROBLEM 59 Calculate the escaped CO_2 during the transport of water sample from field to laboratory, using the chemical data of groundwater shown in Table 59.1.

Key Concept During the transport of the water sample from field to laboratory, some amount of carbon dioxide can be escaped. This clearly reflects on the analysis of chemical composition of groundwater. Thus, the water quality analysis must be done immediately after the collection of the water samples.

Data of the given problem

TABLE 59.1 Chemical Data of Groundwater

Parameter	*Field data*	*Laboratory data*
Temperature (°C)	23	34
pH	6.6	8.2
HCO_3^- (mg/l)	240	200

Solution (see Appendix XVI)

Calculation of escaped CO_2:

$$\log P_{CO_2} = 7.82 + \log mHCO_3^- - pH \qquad (59.1)$$

where,

m = concentration in moles per litre of the concerned ion

$$= \frac{\text{Concentration in mgl} \times \text{Conversion factor}}{1{,}000} \qquad (59.2)$$

Therefore, $\log P_{CO_2} = \text{Field } HCO_3^- = \frac{240 \times 0.01639}{1{,}000} = 0.003936$

Therefore, $\log P_{CO_2} = \text{Laboratory } HCO_3^- = \frac{200 \times 0.01639}{1{,}000} = 0.003278$

$$\begin{aligned}
\text{Field } \log mHCO_3^- &= \log \text{ of } 0.003936 \\
&= -2.405 \\
\text{Laboratory } \log mHCO_3^- &= \log \text{ of } 0.003278 \\
&= -2.484 \\
pH &= \text{value of field pH}
\end{aligned}$$

Therefore, $\text{field } \log P_{CO_2} = 7.82 + (-2.405) - 6.6 = -1.185$

Therefore, $\text{laboratory } \log P_{CO_2} = 7.82 + (-2.484) - 8.2 = -2.864$

Here, the laboratory $P_{CO_2}(10^{-2.864})$ is less than the field $P_{CO_2}(10^{-1.185})$ so that CO_2 is escaped during the transport of water sample from field to laboratory.

PROBLEM 60 Compute the (a) ionic strength of the solution, (b) activity coefficient of an individual ion, (c) chemical activity of an individual ion and (d) saturation indices of $CaCO_3$, $CaMg(CO_3)_2$, $CaSO_4$, NaCl and CaF_2 from the chemical data of the groundwater samples shown in Table 60.1.

Key Concept Saturation index is an index showing whether the water will tend to dissolve (*undersaturation state*) or equilibrate (*saturation state*) or precipitate (*oversaturation state*) a particular mineral. In very dilute water solutions, the molal concentrations can be used to determine equilibrium and solubility. Chemical activities must be computed from the concentration before the law of mass action can be applied, as the electrostatic forces cause the behaviour of the solutes to be non-ideal.

Data of the given problem

TABLE 60.1 Chemical Composition of Groundwater

Chemical variables	*Sample numbers*					
	1	2	3	4	5	6
Temperature (^oC)	21	20	23	23	24	26
pH	8.2	8.3	8.0	7.9	7.8	6.8
Calcium, Ca^{2+} (mg/l)	70	80	40	80	100	110
Magnesium, Mg^{2+} (mg/l)	30	80	35	70	85	80
Sodium, Na^+ (mg/l)	55	91	291	330	430	542
Potassium, K^+ (mg/l)	1	9	19	27	22	39
Bicarbonate, HCO_3^- (mg/l)	440	520	210	225	450	235
Carbonate, CO_3^{2-} (mg/l)	–	25	–	–	–	–
Chloride, Cl^- (mg/l)	15	85	225	460	715	950
Sulphate, SO_4^{2-} (mg/l)	23	120	365	243	126	243
Nitrate, NO_3^- (mg/l)	9	26	31	233	55	72
Fluoride, F^- (mg/l)	1.0	1.7	0.8	1.1	1.2	0.9

Solution

(a) Computation of ionic strength: The ionic strength of the solution must be determined in order to compute the activity coefficient of an individual ion.

$$I = \frac{1}{2}\sum m_i z_i^2 \tag{60.1}$$

where,

I = ionic strength
m_i = molality of ith ion
z_i = charge of ith ion

Conversion of meq/l to molarity: It is shown below:

$$\text{Molarity} = \frac{\text{Concentration in meq/l}}{1{,}000} \tag{60.2}$$

For example, Ca^{2+} in sample 1 = $\dfrac{3.493}{1{,}000}$ = 0.003493

TABLE 60.2 Values of Molarity Computed from Values of meq/l (Table 56.3)

Chemical variable	1	2	3	4	5	6
Ca^{2+}	0.003493	0.003992	0.001996	0.003992	0.004990	0.005491

Mg^{2+}	0.002478	0.006581	0.002879	0.005758	0.006992	0.006581
Na^+	0.002393	0.003959	0.012659	0.014355	0.018705	0.023578
K^+	0.000026	0.000230	0.000486	0.000690	0.000563	0.000997
HCO_3^-	0.007212	0.008523	0.003442	0.003688	0.007376	0.003852
CO_3^{2-}	–	0.000833	–	–	–	–
Cl^-	0.000423	0.002398	0.006347	0.012977	0.020170	0.026800
SO_4^{2-}	0.000479	0.002498	0.007600	0.005059	0.002623	0.005059
NO_3^-	0.000145	0.000419	0.000500	0.003758	0.000887	0.001161
F^-	0.000053	0.000089	0.000042	0.000058	0.000063	0.000047

Computation of ion concentration as per charge of ion (z_i): It is shown in Table 60.3:

TABLE 60.3 Computation of Ion Concentration, as Per z_i (Ion Valency)

Chemical variable	z_i	1	2	3	4	5	6
Ca^{2+}	2	0.006986	0.007984	0.003992	0.007984	0.009980	0.010982
Mg^{2+}	2	0.004956	0.013162	0.005758	0.011516	0.013984	0.013162
Na^+	1	0.002393	0.003959	0.012659	0.014355	0.018705	0.023578
K^+	1	0.000026	0.000230	0.000486	0.000690	0.000563	0.000997
HCO_3^-	1	0.007212	0.008523	0.003442	0.003688	0.007376	0.003852
CO_3^{2-}	2	–	0.001666	–	–	–	–
Cl^-	1	0.000423	0.002398	0.006347	0.012977	0.020170	0.026800
SO_4^{2-}	2	0.000958	0.004996	0.015200	0.010112	0.005246	0.010118
NO_3^-	1	0.000145	0.000419	0.000500	0.003758	0.000887	0.001161
F^-	1	0.000053	0.000089	0.000042	0.000058	0.000063	0.000047
Total		0.023152	0.043426	0.048426	0.065138	0.076957	0.090697

Calculation of ionic strength (*I*): It is calculated using the following formula:

$$I = \frac{\text{Total ionic concentration}}{2} \tag{60.3}$$

Table 60.4 shows the calculation of ionic strength.

TABLE 60.4 Calculations of Ionic Strength (Table 60.3)

	1	2	3	4	5	6
I	0.012	0.022	0.024	0.033	0.038	0.045
$\sqrt{I}$	0.110	0.148	0.155	0.182	0.195	0.212

(b) Computation of activity coefficient: Once the ionic strength of a solution of electrolytes is known, the activity coefficient of the individual ion can be determined following the Debye–Huckel equation, as shown below:

$$-\log \gamma_i = \frac{A z_i^2 \sqrt{I}}{1 + a_i B \sqrt{I}} \tag{60.4}$$

where,

γ_i = activity coefficient of ionic species i
z_i = charge of ith ion
I = ionic strength of the solution
A = constant equal to 0.5085 at 25°C
B = constant equal to 0.3281 at 25°C
a_i = effective diameter of the ion (Table 60.5)

TABLE 60.5 Values of Parameter a_i in the Debye–Huckel Equation

a_i	*Ion*
11	Th^{4+}, Sn^{4+}
9	Al^{3+}, Fe^{3+}, Cr^{3+}, H^{3+}
8	Mg^{2+}, Be^{2+}
6	Ca^{2+}, Cu^{2+}, Zn^{2+}, Sn^{2+}, Mn^{2+}, Fe^{2+}, Ni^{2+}, Co^{2+}, Li^{2+}
5	$Fe(CN)_6^{4-}$, Sr^{2+}, Ba^{2+}, Cd^{2+}, Hg^{2+}, S^{2-}, Pb^{2+}, CO_3^{2-}, SO_3^{2-}, MoO_4^{2-}
4	PO_4^{3-}, $Fe(CN)_6^{3-}$, Hg_2^{2+}, SO_4^{2-}, SeO_4^{2-}, CrO_4^{3-}, HPO_4^{2-}, Na^+, HCO_3^-, $H_2PO_4^-$
3	OH^-, F^-, CNS^-, CNO^-, HS^-, ClO_4^-, K^+, Cl^-, Br^-, I^-, CN^-, NO_2^-, NO_3^-, Rb^+, Cs^+, NH_4^+, Ag^+

(c) Computation of chemical activity: The chemical activity of an ion is equal to the molal concentrations times a factor known as the *activity coefficient*.

$$\alpha = \gamma m \tag{60.5}$$

where,

α = chemical activity
γ = activity coefficient
m = molal concentration

Now we will compute activity coefficient $(-\log \gamma_i)$ and chemical activity (α) of Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-} and F^- following Eqs. (60.4) and (60.5), respectively.

Computation of activity coefficient ($-\log \gamma_i$) and chemical activity (α) of Ca^{2+}: It is given below:

$$-\log \gamma_{Ca^{2+}} = \frac{0.5085\,(2)^2\,(0.110)}{1+0.3281\,(6)(0.110)}$$

Therefore, $-\log \gamma_{Ca^{2+}} = \dfrac{0.22374}{1.216546} = -0.184$

antilog $\gamma_{Ca^{2+}} = 1.000 - 0.184 = 0.816$

$\gamma_{Ca^{2+}} = 0.655$ (see antilog value for 0.816)

$\alpha_{Ca^{2+}} = 0.003493 \times 0.655 = 0.00229$ or $-0.2.64$ or $10^{-2.64}$

Computation of activity coefficient ($-\log \gamma_i$) and chemical activity (α) of Mg^{2+}: It is given below:

$$-\log \gamma_{Mg^{2+}} = \frac{0.5085\,(2)^2\,0.110}{1+0.3281\,(8)\,(0.110)}$$

Therefore, $-\log \gamma_{Mg^{2+}} = \dfrac{0.22374}{1.288728} = -0.174$

antilog $\gamma_{Mg^{2+}} = 1.000 - 0.174 = 0.826$

$\gamma_{Mg^{2+}} = 0.670$ (see antilog value for 0.826)

$\alpha_{Mg^{2+}} = 0.002478 \times 0.670 = 0.00166$ or $-0.\ 2.78$ or $10^{-2.78}$

Computation of activity coefficient ($-\log \gamma_i$) and chemical activity (α) of Na^{+}: It is given below:

$$-\log \gamma_{Na^{+}} = \frac{0.5085\,(1)^2\,(0.110)}{1+0.3281\,(4)\,(0.110)}$$

Therefore, $-\log \gamma_{Na^{+}} = \dfrac{0.055935}{1.144364} = -0.0489$

antilog $\gamma_{Na^{+}} = 1.000 - 0.0489 = 0.951$

$\gamma_{Na^{+}} = 0.893$ (see antilog value for 0.951)

$\alpha_{Na^{+}} = 0.002393 \times 0.893 = 0.00214$ or -2.67 or $10^{-2.67}$

Computation of activity coefficient $(-\log \gamma_i)$ and chemical activity (α) of HCO_3^-: It is given below:

$$-\log \gamma_{HCO_3^-} = \frac{0.5085\,(1)^2\,(0.110)}{1 + 0.3281\,(4)\,(0.110)}$$

Therefore, $$-\log \gamma_{HCO_3^-} = \frac{0.055935}{1.44364} = -0.0489$$

$$\text{antilog } \gamma_{HCO_3^-} = 1.000 - 0.0489 = 0.951$$

$$\gamma_{HCO_3^-} = 0.893 \text{ (see antilog value for 0.951)}$$

$$\alpha_{HCO_3^-} = 0.007212 \times 0.893 = 0.00644 \quad \text{or} \quad -2.19 \text{ or } 10^{-2.19}$$

Computation of activity coefficient $(-\log \gamma_i)$ and chemical activity (α) of CO_3^{2-}: It is given below:

$$-\log \gamma_{CO_3^{2-}} = \frac{0.5085\,(2)^2\,(0.110)}{1 + 0.3281\,(5)\,(0.110)}$$

Therefore, $$-\log \gamma_{CO_3^{2-}} = \frac{0.22374}{1.180455} = -0.190$$

$$\text{antilog } \gamma_{CO_3^{2-}} = 1.000 - 0.190 = 0.810$$

$$\gamma_{CO_3^{2-}} = 0.646 \text{ (see antilog value for 0.810)}$$

$$\alpha_{CO_3^{2-}} = 0.000833 \times 0.646 = 0.00054 \text{ or } -3.27 \text{ or } 10^{-3.27}$$

$$\text{Molality of } CO_3^{2-} = \frac{\alpha_H + \alpha_{CO_3^{2-}}}{\alpha_{HCO_3^-}} \tag{60.6}$$

$$\text{Molality of } CO_3^{2-} = 10^{-10.3}$$

From pH, $$\alpha_{H^+} = \frac{10^{-10.3} \times 10^{-2.19}}{10^{-8.2}} = 10^{-4.29}$$

Computation of activity coefficient $(-\log \gamma_i)$ and chemical activity (α) of Cl^-: It is given below:

$$-\log \gamma_{Cl^-} = \frac{0.5085\,(1)^2\,(0.110)}{1 + 0.3281\,(3)\,(0.110)}$$

Therefore, $$-\log \gamma_{Cl^-} = \frac{0.055935}{1.108273} = -0.0505$$

$$\text{antilog } \gamma_{Cl^-} = 1.000 - 0.0504 = 0.950$$

$$\gamma_{Cl^-} = 0.891 \text{ (see antilog value for 0.950)}$$

$$\alpha_{Cl^-} = 0.000423 \times 0.891 = 0.000377 \quad \text{or} \quad -3.42 \text{ or } 10^{-3.42}$$

Computation of activity coefficient ($-\log \gamma_i$) and chemical activity (α) of SO_4^{2-}: It is given below:

$$-\log \gamma_{SO_4^{2-}} = \frac{0.5085\,(2)^2\,(0.110)}{1 + 0.3281\,(4)\,(0.110)}$$

Therefore,
$$-\log \gamma_{SO_4^{2-}} = \frac{0.22374}{1.144364} = -0.196$$

$$\text{antilog } \gamma_{SO_4^{2-}} = 1.000 - 0.196 = 0.804$$

$$\gamma_{SO_4^{2-}} = 0.637 \text{ (see antilog value for 0.804)}$$

$$\alpha_{SO_4^{2-}} = 0.000479 \times 0.637 = 0.000305 \quad \text{or} \quad -3.52 \quad \text{or} \quad 10^{-3.52}$$

Computation of activity coefficient (- log g_i) and chemical activity (a) of F^-: It is shown below

$$-\log \gamma_{F^-} = \frac{0.5085\,(1)^2\,(0.110)}{1 + 0.3281\,(3)\,(0.110)}$$

Therefore,
$$-\log \gamma_{F^-} = \frac{0.055935}{1.108273} = -0.0505$$

$$\text{antilog } \gamma_{F^-} = 1.000 - 0.0504 = 0.950$$

$$\gamma_{F^-} = 0.891 \text{ (see antilog value for 0.950)}$$

$$\alpha_{F^-} = 0.000053 \times 0.891 = 0.000047 \quad \text{or} \quad -4.33 \quad \text{or} \quad 10^{-4.33}$$

Now, we will compute saturation indices (SI) of $CaCO_3$, $CaMg(CO_3)_2$, $CaSO_4$, NaCl and CaF_2. But, first we disays what saturation index means and how it is calculated.

Saturation index (SI) is an index showing whether the water will tend to dissolve or precipitate a particular mineral. The saturation index is calculated by comparing the chemical activities of the dissolved ions of the mineral (*ion activity product*) with their *solubility product*.

Saturation index (SI) can be defined as the ratio of the mineral solubility product to its ion activity product.

$$SI = \frac{K_{IAP}}{K_{SP}} \tag{60.7}$$

where,

K_{IAP} = ion activity product

K_{SP} = solubility product

If SI is negative, it indicates undersaturation (dissolution) state; if SI is zero, it shows equilibrium (saturation) state; and if it is positive, it shows oversaturation (precipitation) state with respect to the concenred solid phase.

(d) Computation of saturation index of $CaCO_3$: As ion activity product (K_{IAP}) is the product of chemical activity of the mineral phase. It is as follows:

$$\text{Ion activity product } (K_{IAP}) \text{ of } CaCO_3 = (\alpha_{Ca^{2+}})(\alpha_{CO_3^{2-}}) \tag{60.8}$$

$$K_{IAP} = 10^{-2.64} \times 10^{-4.29} = 10^{-6.93}$$

$$\text{Solubility product } (K_{SP}) \text{ of } CaCO_3 = 10^{-8.35}$$

$$\frac{K_{IAP}}{K_{SP}} = \frac{10^{-6.93}}{10^{-8.35}}$$

$$\text{Therefore,} \qquad \text{saturation index of } CaCO_3 = 1.42$$

Computation of saturation index of $CaMg(CO_3)_2$: It is shown below:

$$\text{Ion activity product } (K_{IAP}) \text{ of } CaMg(CO_3)_2 = (\alpha_{Ca^{2+}})(\alpha_{Mg^{2+}})(\alpha_{CO_3^{2-}})$$

$$K_{IAP} = 10^{-2.64} \times 10^{-2.78} \times 10^{-4.29} = 10^{-9.71}$$

$$\text{Solubility product } (K_{SP}) \text{ of } CaMg(CO_3)_2 = 10^{-17.0}$$

$$\frac{K_{IAP}}{K_{SP}} = \frac{10^{-9.71}}{10^{-4.50}}$$

$$\text{Therefore,} \qquad \text{saturation index of } CaMg(CO_3)_2 = 7.29$$

Computation of saturation index of $CaSO_4$: It is as below:

$$\text{Ion activity product } (K_{IAP}) \text{ of } CaSO_4 = (\alpha_{Ca^{2+}})(\alpha_{SO_4^{2-}})$$

$$K_{IAP} = 10^{-2.64} \times 10^{-3.52} = 10^{-6.16}$$

$$\text{Solubility product } (K_{SP}) \text{ of } CaSO_4 = 10^{-4.50}$$

$$\frac{K_{IAP}}{K_{SP}} = \frac{10^{-6.16}}{10^{-4.50}}$$

$$\text{Therefore,} \qquad \text{saturation index of } CaSO_4 = -1.66$$

Computation of saturation index of NaCl: It is shown follows:

$$\text{Ion activity product } (K_{IAP}) \text{ of NaCl} = (\alpha_{\mathrm{Na}^+})(\alpha_{\mathrm{Cl}^-})$$

$$K_{IAP} = 10^{-2.67} \times 10^{-3.42} = 10^{-6.09}$$

$$\text{Solubility product } (K_{SP}) \text{ of NaCl} = 10^{-1.60}$$

$$\frac{K_{IAP}}{K_{SP}} = \frac{10^{-6.09}}{10^{-1.60}}$$

Therefore, $\text{saturation index of NaCl} = -4.49$

Computation of saturation index (SI) of CaF_2: It is as below:

$$\text{Ion activity product } (K_{IAP}) \text{ of } \mathrm{CaF_2} = (\alpha_{\mathrm{Ca}^{2+}})(\alpha_{\mathrm{F}^-})$$

$$K_{IAP} = 10^{-2.64} \times 10^{-4.33} = 10^{-6.97}$$

$$\text{Solubility product } (K_{SP}) \text{ of } \mathrm{CaF_2} = 10^{-10.40}$$

$$\frac{K_{IAP}}{K_{SP}} = \frac{10^{-6.97}}{10^{-10.40}}$$

Therefore, $\text{saturation index of } \mathrm{CaF_2} = 3.43$

TABLE 60.6 Calculated SI of $CaCO_3$, $CaMg(CO_3)_2$, $CaSO_4$, NaCl and CaF_2 for All Groundwater Samples of Table 60.1

Saturation index	*Sample numbers*					
	1	2	3	4	5	6
$CaCO_3$	1.42	1.65	0.66	0.89	1.18	0.05
$CaMg(CO_3)_2$	7.29	7.94	6.60	7.13	7.50	6.24
$CaSO_4$	–1.66	–0.88	–0.70	–0.57	–0.77	–0.43
NaCl	–4.49	–3.66	–2.60	–2.23	–1.92	–1.70
CaF_2	3.43	3.72	3.09	3.53	3.66	3.58

The groundwater shows oversaturation (+) with respect to $CaCO_3$ (0.05 to 1.65), $CaMg(CO_3)_2$ (6.24 to 7.94) and CaF_2 (3.09 to 3.72), indicating a precipitation state of calcite ($CaCO_3$), dolomite [$CaMg(CO_3)_2$] and fluorite (CaF_2), and undersaturation (–) with respect to $CaSO_4$ (–0.43 to –1.66) and NaCl (–1.70 to –4.49), indicating a dissolution state of anhydrite ($CaSO_4$) and halite (NaCl), respectively (Table 60.6).

Appendix I

Rain-gauge Density, Runoff and Runoff Coefficient Factor

Here, Table I.1 shows the rain-gauge density for various types of areas. Table I.2 depicts Barlow's classification of catchment on the basis of monsoon from the average condition. Based on civil constructions, the values of runoff coefficient factor (*K*) are shown in Table I.3, and Table I.4 shows the values of *N* for various sizes of catchment.

TABLE I.1 Rain-gauge Density (ISI, 1969)

Area	*Rain-gauge density*
Plains	1 for 520 km^2
Elevated area	1 for 260 km^2 to 390 km^2
Hilly and very heavy rainfall areas	1 for 130 km^2 preferably with 10% of the rain-gauge stations equipped with the self-recording type

TABLE I.2 Barlow's (1915) Classification of Catchment Based on Monsoon from the Average Condition

Nature of season	*Class*				
	A	*B*	*C*	*D*	*E*
Light rainy of no heavy shower	0.70	0.80	0.80	0.80	0.80
Average or varying rainfall, no continuous down pour	1.00	1.00	1.00	1.00	1.00
Continuous downpour	1.50	1.50	1.60	1.70	1.80

TABLE I.3 Runoff Coefficient Factor (*K*) Based on Civil Constructions

Area	*Runoff coefficient (K)*
Urban residential and single houses	0.30
Garden apartments	0.50
Commercial and industrial	0.90
Parks, farmlands and pastures	0.05–0.30
Asphalt or concrete pavement	0.85

TABLE I.4 Values of *N* for Various Sizes of Catchments (Linsley et al., 1949)

Drainage area (km^2)	*N days*
250	2
1,250	3
5,000	4
12,500	5
25,000	6

$$N = 0.83\,(A_d)^{0.2} \text{ (Davis and Dewiest, 1966)}$$

where,

N = days, depending on the slope, shape and area of the drainage basin
A_d = drainage area (km^2)

APPENDIX II

Watershed and Types of Drainage Pattern

Watershed is defined as a geohydrological unit draining to a common point by a system of drains. All lands on the earth are part of one watershed or other. Watershed, is thus, the land and water area, which contributes runoff to a common point. A watershed is an area of land and water bounded by a drainage divide within which the surface runoff collects and flows out of the watershed through a single outlet into a lager river (or) lake. Watershed approach is considered ideal for management and utilisation of three basic natural resources, i.e., land, water and vegetation and their interaction in the context of watershed boundaries.

II.1 CLASSIFICATION OF WATERSHED

A watershed is classified depending upon the size, drainage, shape and land use pattern (Table II.1).

TABLE II.1 Classification of Watershed

Classification	*Area covered* (km^2)
Macro-watershed	> 500
Sub-watershed	100 to 500
Milli-watershed	10 to 100
Micro-watershed	1 to 10
Mini-watershed	< 1

II.2 TYPES OF DRAINAGE PATTERN

Natural drainage patterns are created, where stream courses follow the lead of a landscape's geological history and features. Characteristics of the underlying rock, steepness of slope, faults and joints in the Earth's surface, specific shape of particular geological formations, and soil's susceptibility to erosion are among the factors that affect the pattern established for the flow of water in a particular place. Generally, drainage patterns are of six types. They are (a) dendritic drainage pattern, (b) trellis drainage pattern, (c) radial drainage pattern, (d) parallel drainage pattern, (e) rectangular drainage pattern and (f) annular drainage pattern, as shown in Figure II.1.

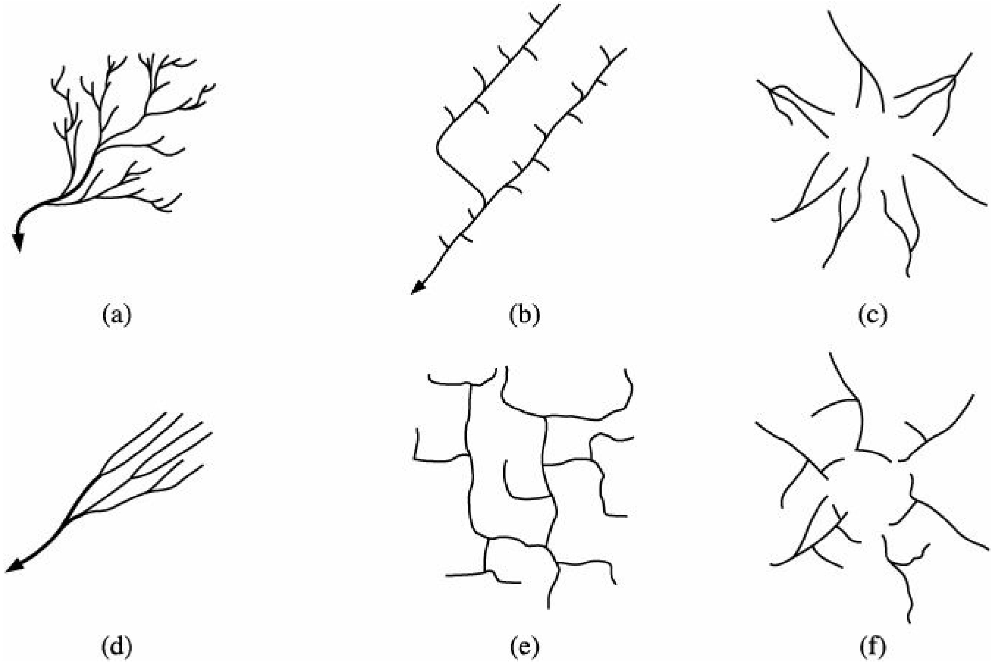


FIGURE II.1 (a) Dendritic drainage pattern, (b) Trellis drainage pattern, (c) Radial drainage pattern, (d) Parallel drainage pattern, (e) Rectangular drainage pattern and (f) Annular drainage pattern.

Dendritic drainage pattern

Dendritic drainage system (*dendrites* means of or pertaining to a tree) is the most common form of drainage system (Figure II.1a). It has many contributing streams (analogous to the twigs of a tree), which are then joined together into the tributaries of the main river (the branches and the trunk of the tree, respectively). They develop, where the river channel follows the slope of the terrain. Dendritic systems form in V-shaped valleys; as a result, the rock types must be impervious and non-porous.

Trellis drainage pattern

The geometry of a trellis drainage system is similar to that of a common garden trellis used to grow vines (Figure II.1b). As the river flows along a strike valley, smaller tributaries feed into it from the steep slopes on the sides of mountains. These tributaries enter the main river at approximately 90° angle, causing a trellis-like appearance of the drainage system. Trellis drainage is a characteristic of folded mountains.

Radial drainage pattern

In a radial drainage system, the streams radiate outwards from a central high point (Figure II.1c). Volcanoes usually display excellent radial drainage. Other geological features on which radial drainage commonly develops are domes and laccoliths. On these features, the drainage exhibits a combination of radial patterns.

Parallel drainage pattern

A parallel drainage system is a pattern of rivers caused by steep slopes with some relief (Figure II.1d). Because of the steep slopes, the streams are swift and straight, with very few tributaries, and all flow in the same direction. This system forms on uniformly sloping surfaces.

Rectangular drainage pattern

Rectangular drainage develops on rocks, which are of approximately uniform resistance to erosion, but have two directions of joining at approximately right angles (Figure II.1e). The joints are usually less resistant to erosion than the bulk rock; so, erosion tends to preferentially open the joints and streams eventually develop along the joints. The result is a stream system in which streams mainly consist of straight line segments with right angle bends and tributaries join larger streams at right angles.

Annular drainage pattern

In an annular drainage pattern, streams follow a roughly circular or concentric path along a belt of weak rock, resembling a ring-like pattern (Figure II.1f). It is best displayed by streams draining a maturely dissected structural dome or basin, where erosion has exposed rimming sedimentary strata of greatly varying degrees of hardness, which nearly encircles the domal structure.

Appendix III

Hypsometric Analysis

Hypsometric analysis (HA) is first introduced by Langebein (1947) to explain the overall slope and the forms of drainage basin. It is an important tool to assess and compare the geomorphic evolution of various landforms (Strahler, 1952). The HA is expressed in terms of (a) hypsometric curve (HC) and (b) hypsometric integral (Hi). The HC is widely used directly to compare different watersheds and indirectly to assess their distribution of area relative to relief. It is also possible to compare the evolution of the landscapes and directly compare degrees of dissection (assuming all the basins began with a similar distribution of area versus relief). According to Strahler (1952), a convex-shaped HC characterises youth stage of watershed, an S-shaped HC (that is concave upwards at higher elevations and convex downwards at lower elevations) indicates mature stage of watershed and a concave HC characterises old stage or peneplain watershed (Figure III.1a). The HC is related to the volume of soil mass in a basin and the amount of erosion that occurs in a basin against the remaining mass. This is a continuous function of non-dimensional distribution of relative basin with a relative area of the drainage basin. This surface elevation can be useful to topographic comparisons because of its revelation of 3D information through 2D approach. As comparisons of the shape of the HC for different basins under a similar hydrological conditions provide a relative insight into the past soil movement in the basins, the shape of the HC explains the temporal changes in the slope of the original basin.

The Hi is an indication of the cycle of the erosion (Strahler, 1952). The cycle of the erosion is the total time required for reduction of land area to the base level (Figure III.1b). This cycle can be divided into three stages—(a) the first one is called *monadnock or old stage*, in which the Hi is less than 0.30, and the watershed is fully stabilised that means tectonically stable, (b) the second one is called *equilibrium* or *mature stage*, in which the Hi varies from 0.30 to 0.60, and (c) the last one is referred to as *inequilibrium* or *young* *stage*, in which the Hi is more than 0.60, and the watershed is highly susceptible to erosion that means unstable and actively uplifted.

The Hi number ranges from 0 and 1. A low hypsometric integral value suggests the old, eroded, evenly dissected drainage basins. High values of the hypsometric integral indicate that most of the topography is less eroded and high relative to the mean elevation such as young uplifted ranges cut by deeply incised streams. According to W.M. Davis (1899), the Hi values less than 0.30 describe tectonically stable, denuded, mature basins; the Hi values more than 0.60 indicate unstable, actively uplifting, young basins. Willgoose and Hancock (1998) have a slightly different opinion on Hi. They consider values more than 0.50 dominated by diffusive processes (mainly, hill slope processes). The Hi values less than 0.50 are considered dominated by fluvial erosion (channel processes play a larger role). More balanced, flattened S-shaped, or straight hypsometric curves (Hi ~0.50) suggest a relatively stable, but still developing landscape. Thus, the hypsometric integral is large in the youth stage, but it decreases as the landscape is denuded towards a stage of maturity and old stage.

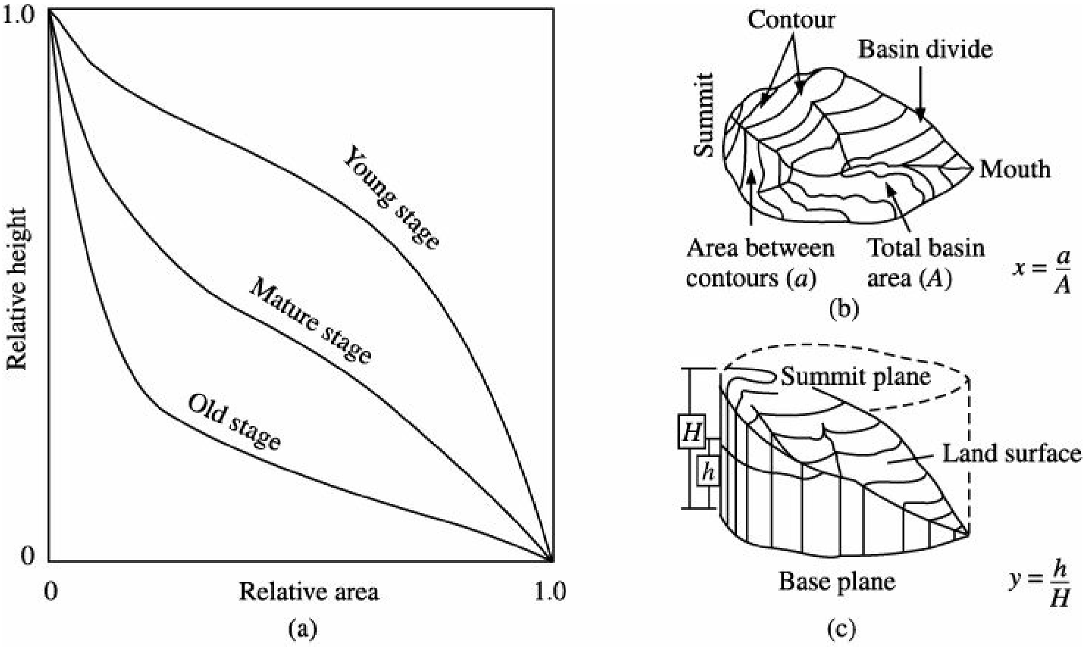


FIGURE III.1 Concept of the hypsometric analysis.

Thus, the HC reveals the stages of geomorphic development of the watershed, while the Hi explains the geological stages of development and soil erosion in the watershed.

Appendix IV

Classification of Soils and Grain Size with Respect to Porosity

In this appendix, some information (in the form of tables and figures) is provided regarding the diameter of sieve opening with respect to Indian Standard sieve number (Table IV.1); triangles of soil textures (Figure IV.1); porosity, specific yield and specific retention with respect to soil (Table IV.2); variations of porosity, specific yield and specific retention with grain size (Figure IV.2); specific yield values in different geological formations (Table IV.3); bulk modulus of compression of selected formation materials (Table IV.4); quantity of dye required for groundwater velocity measurement (Table IV.5); doses of salt tracers required for injection into the well in relation to distance between injection well and observation well (Table IV.6); permeability of some materials (Table IV.7); estimation of groundwater resources in India (Table IV.8); and classification of areas based on level of groundwater development (Table IV.9).

TABLE IV.1 Diameter of Sieve Opening with Respect to Indian Standard Sieve Number

Serial number	*Indian Standard sieve number*	*Diameter (D) of sieve opening* (mm)
1	240	2.399
2	120	1.201
3	60	0.592
4	30	0.296
5	15	0.151
6	8	0.075
7	Pan	–

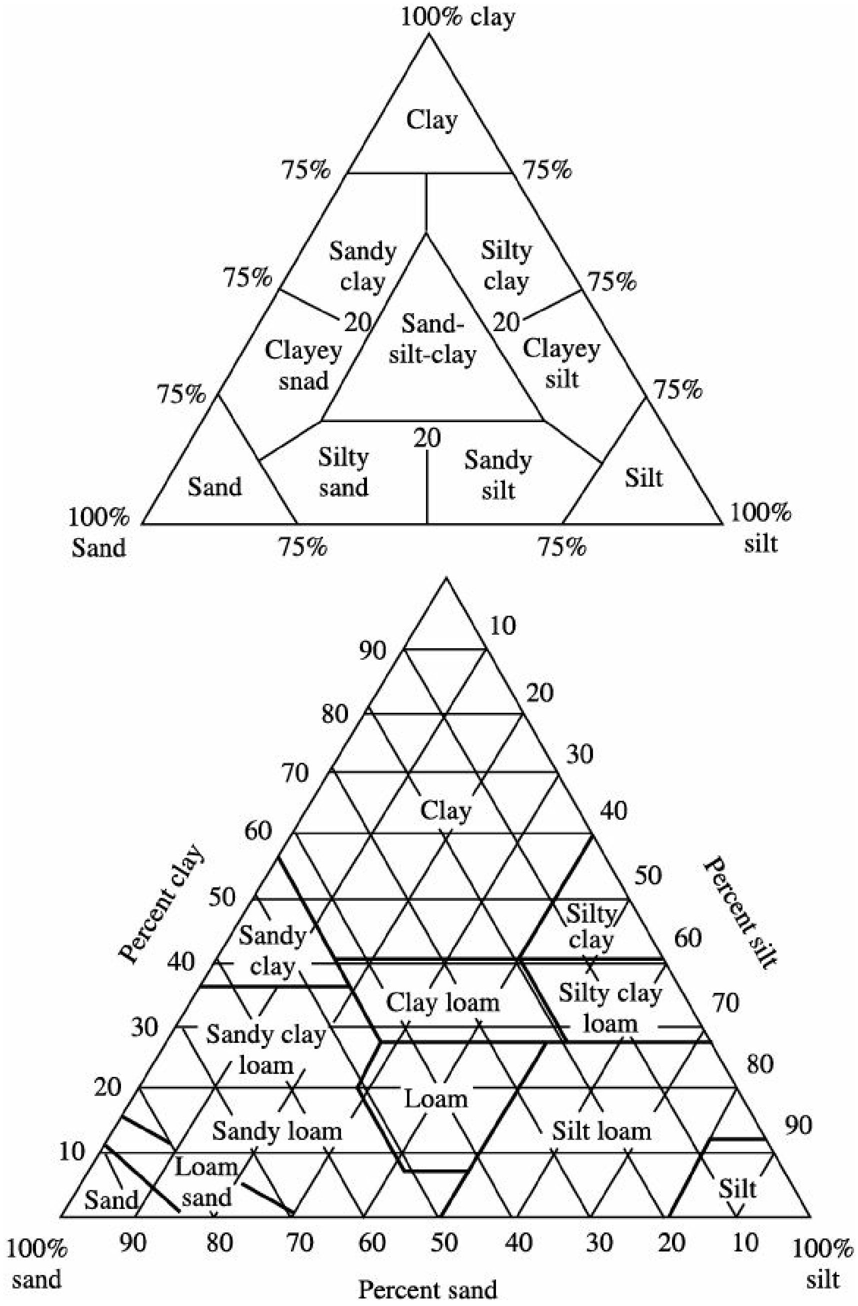


FIGURE IV.1 Triangle of soil textures.

TABLE IV.2 Porosity, Specific Yield and Specific Retention with Respect to Soil

Material	*Porosity*	*Specific yield*	*Specific retention*
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1

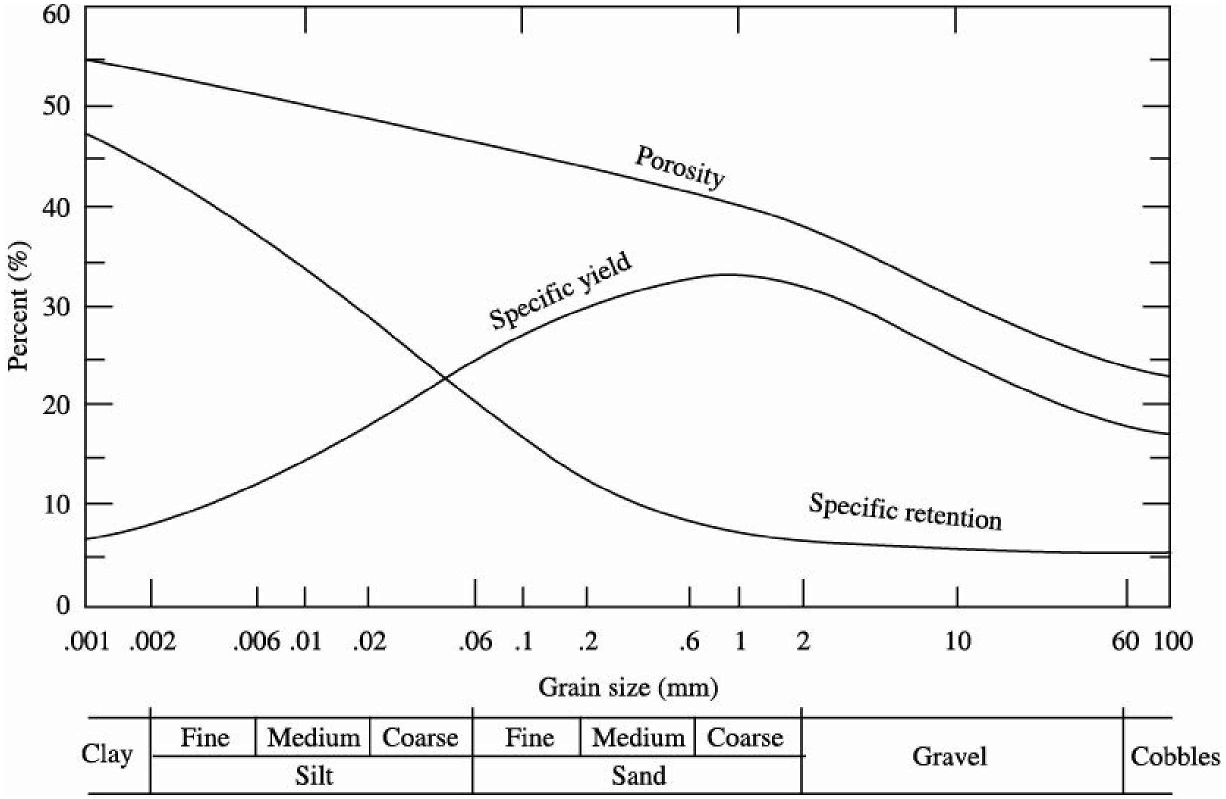


FIGURE IV.2 Variations of porosity, specific yield and specific retention with grain size.

TABLE IV.3 Specific Yield Values in Different Geological Formations

Geological formations	*Percent*
Sandy alluvial area	12 to 18
Valley fills	10 to 14
Silty/clayey alluvial area	5 to 12
Granites	2 to 4
Basalts	1 to 3
Laterite	2 to 4
Weathered phyllites, shales, schist and associated rocks	1 to 3
Sandstone	1 to 8
Limestone	3
Highly karstified limestone	7

TABLE IV.4 Bulk Modulus of Compression of Selected Formation Materials

Material	*Bulk modulus of compression of elasticity* (km/m^2)
Dense rock	1×10^9 to 1×10^{11}
Fissured rock	1×10^8 to 1×10^{10}
Dense sand	5×10^8 to 8×10^6

Loose sand	1×10^6 to 2×10^6
Stiff clay	4×10^5 to 8×10^5
Plastic clay	5×10^4 to 4×10^5

TABLE IV.5 Quantity of Dye Required for Groundwater Velocity Measurement (UNESCO, 1972)

Dye	*Quantity* (g) *of dye per* 10 m *of flow path*			
	Clay	*Sand*	*Fractured rock*	*Karst*
Fluorescein	5 to 20	2 to 10	2 to 20	2 to 10[a]
Eosin	5 to 20	2 to 10	2 to 20	2 to 10[a]
Erythrosine	10 to 40	10 to 30	10 to 40	10 to 40[a]
Methylene blue	20 to 80	20 to 60	20 to 80	20 to 80[b]

[a] for alkaline waters; *b* for acidic waters

TABLE IV.6 Doses of Salt Tracers Required for Injection into the Well in Relation to Distance between Injection Well and Observation Well (UNESCO, 1972)

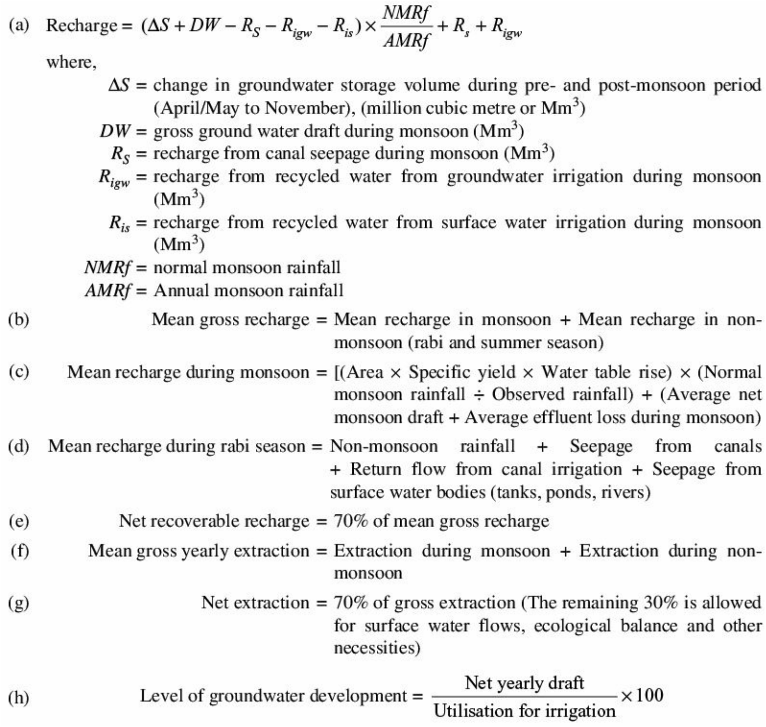
Salt	*Recommended dose* (kg)	*Distance* (m)
Sodium chloride	10 to 15	5 to 7
Lithium chloride	0.01 to 0.02	2 to 5
Calcium chloride	5 to 10	3 to 5

TABLE IV.7 Permeability of Some Materials

Material	*Permeability* (m/day)
Surface clay soil	0.01 to 0.2
Deep clay beds	10^{-8} to 10^{-2}
Surface loam soil	0.1 to 1
Fine sand	1 to 5
Medium sand	5 to 20
Coarse sand	20 to 100
Gravel	100 to 1,000
Sand and gravel mixes	5 to 100
Clay, sand and gravel mixes	0.001 to 0.1
Sandstone	0.001 to 1
Carbonate rocks with porosity	0.01 to 1
Shale	10^{-7}
Solid rock	$< 10^{-5}$
Fractured or weathered rock	0.001 to 10
Fractured or weathered rock (core)	0 to 300
Volcanic rock	0 to 1,000

TABLE V.8 Estimation of Groundwater Resources in India (2009)

A. Recharge from rainfall	
(a) Alluvial areas	
(i) Sandy areas	20% to 25% of normal rainfall
(ii) Areas with higher clay content	10% to 20% of normal rainfall
(b) Semi-consolidated sandstones (friable and highly porous)	10 to 15% of normal rainfall
(c) Hard rock areas	
(i) Granitic terrain	
• Weathered and fractured	10% to 15% of normal rainfall
• Unweathered	5% to 10% of normal rainfall
(ii) Basaltic Terrain	
• Vesicular and jointed basalt	10% to 15% of normal rainfall
• Weathered basalt	4% to 10% of normal rainfall
(iii) Phyllites, limestones, sandstones, quartzites, shales, etc.	3% to 10% of normal rainfall
B. Recharge due to seepage from unlined canals	
(a) For unlined canals in normal type of soil with some clay content along with sand	15 to 20 ha.m/day/10^6 sq.m of wetted area of canal or 1.8 to 2.5 cumec/10^6 sq.m of wetted area
(b) For unlined canals in sandy soils	25 to 30 ha.m/day/10^6 sq.m of wetted area or 3 to 3.5 cumec/10^6 sq.m of wetted area
(c) For lined canals	the seepage losses may be taken as 20% of the above values
C. Return seepage from irrigation fields	
(a) Irrigation by surface water sources (major irrigation–gravity canals)	35% of water delivered at the outlet for application in the field 40% of water delivered at outlets for paddy irrigation only
(b) Irrigation by groundwater sources (minor irrigation–lift canals, tube wells, etc.)	30% of the water delivered at outlet For paddy irrigation 35% as return seepage of the water delivered may be taken
D. Seepage from tanks	
It is 44 to 60 cm per year over the total water spread. The seepage from percolation tanks is higher and may be taken as 50% of its gross storage. In case of seepage from ponds and lakes, the norms as applied to tanks may be taken.	
E. Recharge during monsoon	
	(a)



(a) Recharge = $(\Delta S + DW - R_S - R_{igw} - R_{is}) \times \dfrac{NMRf}{AMRf} + R_s + R_{igw}$

where,

ΔS = change in groundwater storage volume during pre- and post-monsoon period (April/May to November), (million cubic metre or Mm^3)

DW = gross ground water draft during monsoon (Mm^3)

R_S = recharge from canal seepage during monsoon (Mm^3)

R_{igw} = recharge from recycled water from groundwater irrigation during monsoon (Mm^3)

R_{is} = recharge from recycled water from surface water irrigation during monsoon (Mm^3)

$NMRf$ = normal monsoon rainfall

$AMRf$ = Annual monsoon rainfall

(b) Mean gross recharge = Mean recharge in monsoon + Mean recharge in non-monsoon (rabi and summer season)

(c) Mean recharge during monsoon = [(Area × Specific yield × Water table rise) × (Normal monsoon rainfall ÷ Observed rainfall) + (Average net monsoon draft + Average effluent loss during monsoon)

(d) Mean recharge during rabi season = Non-monsoon rainfall + Seepage from canals + Return flow from canal irrigation + Seepage from surface water bodies (tanks, ponds, rivers)

(e) Net recoverable recharge = 70% of mean gross recharge

(f) Mean gross yearly extraction = Extraction during monsoon + Extraction during non-monsoon

(g) Net extraction = 70% of gross extraction (The remaining 30% is allowed for surface water flows, ecological balance and other necessities)

(h) $$\text{Level of groundwater development} = \frac{\text{Net yearly draft}}{\text{Utilisation for irrigation}} \times 100$$

TABLE IV. 9 Classification of Areas Based on Level of Groundwater Development

Classification	*Stage of development*
White	< 65%
Grey	65 to 85%
Dark	85 to 100%

Appendix V

Well Design and Construction

A well serves as a device for extracting water from an aquifer. A proper well design needs efficient utilisation of aquifer, long service life, low initial cost, low maintenance cost and low operation cost. It depends on the hydrogeological, topographical and climatic conditions. Generally, the samples of the aquifer material are collected from every 1.5 m to 2 m depths or change of stratum as a representative of the entire aquifer for the analysis of well design. The design includes screened production well, well diameter, well depth, well screen and screen material.

V.1 SCREENED PRODUCTION WELL

Screened production well is classified into two types—(a) natural gravel-packed well and (b) artificial gravel-packed well. Materials surrounding the production well are developed in place in the case of the former type to remove the finer material from the aquifer for occurrence of only coarser material surrounding the screen, while those having a coarser uniform grain size than the natural formation are placed artificially around the production well in the case of the latter type to prevent clogging of the pack with fine materials from the aquifer.

For design of the natural gravel-packed wells

a. Non-uniform and relative coarse aquifer material is necessary.
b. Effective grain size (D_{10}) should be more than 0.25 mm.
c. Uniformity coefficient (C_u) should be higher than 2.5.

For design of the artificial gravel-packed wells

a. Uniform and coarse gravel pack is necessary.
b. Effective grain size (D_{10}) should be less than 0.25 mm.
c. Uniformity coefficient (C_u) should be less than 3 for the

homogenous material.

V.2 WELL DIAMETER

Well diameter depends on the installation of the pump suitable for desired discharge with a minimum head loss. According to Dupuit’s formula (1863) for steady state flow, the well yield is

$$Q = C\frac{1}{\log\frac{r_o}{r_w}}$$

where,

Q = well discharge (m^3/day)
C = constant in the equilibrium equation
r_o = radius of the influence (cm)
r_w = radius of the well (cm)

The increase in well diameter can increase the yield marginally. For example, doubling the well diameter from 15 to 30 or 25 to 50 cm under water table conditions (r_w = 150 m) increases the yield from 720 to 7,200 or 2,880 to 28,880 m^3/day, which is 10% only (Table V.1). Thus, increase in the well diameter can increase its cost of construction without a significant increase in well yield. Under confined aquifers, the radius of the influence is larger, which increases the well yield, resulting from doubling the diameter that is even less significant. Generally, the yield in a large-diameter well is more due to the inflow from the well bottom by the occurrence of more water-bearing formations, which are associated with fractures/joints.

TABLE V.1 Discharge versus Well Diameter (Smith, 1961)

Pumping rate (Q)			*Nominal size of pump bowl*	*Well diameter (ID)*	
m^3/min	m^3/hour	m^3/day	cm	cm	m
0.5	30	720	10	15	0.15
1.0	60	1,440	12.5	20	0.20
2.0	120	2,880	15	25	0.25
5.0	300	7,200	20	30	0.30
7.5	450	10,800	25	35	0.35
10.0	600	14,400	30	40	0.40

20.0	1,200	28,880	35	50	0.50
50.0	3,000	72,000	40	60	0.60

The well diameter should be at least 10 cm larger than the diameter of the bowl assembly for installation and efficient operation. And, the well diameter must have a desired percentage of the open area in the length of the screen (15% to 18%) to (a) allow the entrance velocity of 3 to 6 cm/s, (b) reduce the well losses, (c) exclude the finest sand particles (from migrating near the slots) and (d) prevent the incrustation and corrosion at the strainer (well screen) slots. In the deeper wells tapping the confined aquifers, the well diameter can be reduced below the pumping levels during dry climate, where the aquifer heads are relatively high.

V.3 WELL DEPTH

Depth of the well depends on the thickness of the aquifer material, which yields water. Generally, the thickness of the aquifer material decreases with the increase in depth due to the weight of the overlying material. In the hard rock terrain, the depth of the well does not normally exceed 100 m due to the decrease in weathered and fractured rock portions with depth, while it exceeds 1,000 m in the unconsolidated formations due to the occurrence of huge amount of sediments at depth.

Generally, the weathered zone is cased to prevent caving and damage to the pump. If there is an inferior quality of groundwater, such aquifer should be sealed to avoid upward migration of water, where the well is pumped.

V.4 WELL SCREEN

The well screen should be not only resistant to corrosion and deterioration but also strong enough to withstand the column load and collapse pressure. Also, it should prevent excessive movement of sand into the well and have a minimum resistance to the water flow into the well. If the screen has large percentage of the open area, it provides a lower resistance to flow into the well. But, it shows a less structural strength and permits more pumping of sand than a screen with a smaller percentage of the open area.

The influence of the well diameter on well loss is very large, but on aquifer (formation) loss is not very large. However, the total loss, including well loss and aquifer loss, should be minimum, in conjunction with the cost of the screen, boring and the pumping costs required. If the selection of the well diameter is loo large, the cost of the installation will be high, but the running cost will be low, and if it is too small, the cost of the installation will be low and the running cost will be high due to the head loss. Thus, the optimum diameter of the screen depends on the hydraulics of the screen.

Well screen includes screen open area, screen entrance velocity, length of the screen, slot size, screen diameter, and screen material.

V.4.1 Screen Open Area

The selection of the screen open area is for the water to enter the well, which depends on the well loss. The maximum open area can be achieved by providing V-shaped slots, which widen towards the inside of the screen. Thus, the grains do not get lodged in the slots. The greater the percentage of the open area of the screen, the smaller will be the length and diameter of the screen for a given well discharge and velocity. Therefore, the actual open area should be greater than 15% of the total surface area of the screen.

V.4.2 Screen Entrance Velocity

The screen entrance velocity should be kept sufficiently low to ensure a long service life of the well as well as to move an aquifer material, resulting in subsequent clogging of the screen openings. The low aquifer hydraulic conductivity generally consists of fine material compared to high aquifer hydraulic conductivity, which has coarse material. The possibility of clogging depends on the grain size of the fine material in terms of hydraulic conductivity. Table V.2 shows the recommended values for optimum screen entrance velocity for different hydraulic conductivity of the aquifer in natural gravel-packed wells and the average hydraulic conductivity of the aquifer and pack in gravel-packed wells. Thus, the screen entrance velocity of 3 cm/s is generally used.

TABLE V.2 Optimum Screen Entrance Velocity with Respect to Hydraulic Conductivity

Hydraulic conductivity (K)			*Optimum screen entrance velocity*	
m/s	m/hour	m/day	cm/s	m/min
> 0.174	> 10.44	> 250	6.1	3.7
0.174	10.44	250	5.6	3.4

0.139	8.34	200	5.1	3.1
0.111	6.66	160	4.5	2.7
0.104	6.24	150	4.3	2.6
0.083	4.98	120	4.0	2.4
0.069	4.14	100	3.5	2.1
0.056	3.33	80	3.0	1.8
0.042	2.52	60	2.5	1.5
0.035	2.08	50	2.2	1.3
0.028	1.68	40	2.0	1.2
0.014	0.84	20	1.5	0.9
0.014	< 0.84	< 20	1.0	0.6

The screen entrance velocity is determined by dividing the well discharge by the open area through which the water flow occurs.

$$V_e = \frac{Q}{A_s}$$

where,

V_e = screen entrance velocity (m/min)

Q = well discharge (m^3/day)

A_s = effective open area of the screen (m^2)

If the entrance screen velocity is high, it reduces the life of the well by drawing and depositing the fine aquifer material in the artificial gravel-packed wells envelope and clogging the screen openings. In the case of natural gravel-packed wells, rapid clogging of the screen and formation can be prevented by providing sufficient open area on the basis of the well discharge and optimum screen entrance velocity.

$$L_s A_s = \frac{Q}{V_e}$$

where,

L_s = Optimum screen length (m)

A_s = effective open area of the screen (m^2)

Q = well discharge (m^3/day)

V_e = screen entrance velocity (m/min)

V.4.3 Length of the Screen

After deciding the optimum screen velocity and the percentage of the open area of the screen, the length of the screen can be determined. It can be obtained by dividing the expected discharge by the velocity and the open area per unit length of the screen. The open area of the screen should be suitably reduced, where the blocking of the slots is caused by gravel and aquifer material. The length of the well screen depends on the thickness of the aquifer material, available drawdown and stratification of the aquifer material.

$$L_s = \frac{Q}{V_e A_s}$$

where,

L_s = Optimum screen length (m)

Q = well discharge (m^3/day)

V_e = screen entrance velocity (m/min)

A_s = effective open area of the screen (m^2)

In unconfined aquifer

a. The well screen should be placed in the lower $\frac{1}{3}$rd of the thickness of the aquifer material (since the top portion gets desaturated during pumping) to form a hydraulic gradient for flow into the well in the case of homogenous material.
b. In the case of heterogeneous material, the most permeable portion of the lower part of the aquifer should be tapped.

In confined aquifer

a. About 70% to 80% or $\frac{3}{4}$th of the thickness of the aquifer material should be screened and placed in the middle of the aquifer or interspaced with alternating screens and blank sections extending throughout the aquifer in the case of homogenous material.
b. In the case of heterogeneous material, the screen is to be placed

opposite the more permeable strata, leaving about 0.3 m depth at both the top and bottom of the aquifer to prevent the entering of the fine material into the well.

Further, the length of the well screen should be adequate to ensure the acceptable entrance velocity of 3 cm/s or less at design capacity. And, the top of the screen should be set below the lowest pumping level to allow all the possible water level fluctuations.

V.4.4 Slot Size

The selection of the slot size is to prevent the movement of the fine aquifer material near the slots so that all the fines around the well screen can be washed out to improve the aquifer hydraulic conductivity. It depends on the size and gradation of the aquifer material, well discharge and water quality.

If the size of the opening is too large, it allows a fine aquifer material to enter the well and fill it up. If it is too small, it is not possible for the water to enter into the well freely. Thus, the screen grain size (D_{60}) should be taken into account to retain 40% of the formation material outside and the rest to move into the well, which is to be washed out by pumping. But, in practice, the selection of the size of the opening is on the basis of screen grain size of D_{70} to D_{40} or 30 to 60% of the aquifer material.

In natural gravel-packed wells

The slot size of the screen is selected to allow a definite percentage of the material to be passed into the well. The screen is placed in contact with an aquifer material. If there is a fine material in the aquifer close to the screen, it should be removed. Thus, the coarse material surrounding the well increases the porosity and permeability of the formation in the vicinity of the well. It increases the effective well diameter and reduces the entrance velocity of the water, thereby increasing the well effectiveness.

The following are the suggestions for the selection of the slot size:

a. If the uniformity coefficient is more than 6 (a heterogeneous material) and the material overlying the aquifer is fairly firm and will not easily cave, the grain size D_{70} should be selected as the slot size.

b. If the uniformity coefficient is more than 6 (a heterogeneous material) and the material overlying the aquifer is soft and will easily cave, the grain size D_{50} should be selected as the slot size.
c. If the uniformity coefficient is in between 6 and 3 (mostly homogenous material) and the material overlying the aquifer is fairly firm and will not easily cave, the grain size D_{60} should be selected as the slot size.
d. If the uniformity coefficient is in between 6 and 3 (mostly homogenous material) and the material overlying the aquifer is soft and will easily cave, the grain size D_{40} should be selected as the slot size.
e. If there are a number of aquifers of different sizes, the slot size should be selected for the finest aquifer. For example, the grain size D_{50} of the coarsest aquifer is less than four times the grain size D_{50} of the finest aquifer, the slot size or the gravel pack should be on the basis of the finer.
f. If the grain size D_{50} of the coarsest aquifer is more than four times the grain size D_{50} of the finest aquifer, the slot size or gravel pack should be selected separately for each aquifer.
g. If the bottom layers are coarse and the top layers are fine, at least 0.6 m of the screen designed for the fine material should be taken into the coarse stratum below.

In artificial gravel-packed wells

A suitable coarse and uniform gravel pack is placed around the screen not only to improve the discharging capacity of the well by replacement of the finer aquifer material around the screen but also to stabilise the fine-grained and poor aquifers. It permits the use of large slot opening for a better well efficiency in the fine-grained aquifers, and also increases the effective radius of the well. In the case of several aquifers of different sizes, it permits the use of single slot size.

The following are the suggestions for the selection of the slot size:

a. The ratio of the median grain size (D_{50}) of the gravel pack material to the aquifer material $\left(\frac{D_{50} \text{ of gravel pack}}{D_{50} \text{ of acquifer}}\right)$ is taken into consideration to prevent the clogging of the gravel pack with fine material from the aquifer. The ratio is called *gravel pack ratio*.

b. If the uniformity coefficient (C_u) is less than 2, the gravel pack ratio should be in between 9 and 12.5; if it is more than 2, the ratio should be in between 12 and 15.5 to maintain the minimum head loss as well as the minimum sand movement.
c. The gravel pack material should be well-rounded, smooth, clean and uniform, consisting of siliceous grains rather than calcareous ones. The latter particles should not exceed 5% of the total gravel pack material.
d. The gravel pack should be equal to the gravel pack ratio.
e. Two lines should be drawn through these two points so that each gives a uniformity coefficient of 2. The gravel used should be within these enveloping curves.
f. The slot size should be equal to the effective grain size (D_{10}) of the grave pack material to avoid the segregation of fine material near the well screen openings.
g. The width of slots and length vary from 1.5 mm to 4 mm and 5 m to 12.5 cm, respectively.
h. The thickness of the gravel-pack should be in between 10 cm and 20 cm, being an average of 15 cm to retain the aquifer materials effectively.
i. The grain size of the gravel pack material should be less than 10 mm, mostly between 4 mm and 8 mm.
j. If there are more aquifer formations, the gravel pack designed for the finest formation should be arranged for all the formations, provided an average grain size of the material in the coarsest aquifer is less than 4 times the 50% size of the materials in the finest aquifer.

V.4.5 Screen Diameter

Generally, the diameter of the well is kept equal to the diameter of the screen. The diameter of the screen depends on the entrance velocity of the screen, which prevents the incrustation and corrosion as well as minimises the friction losses. The entrance velocity through the screen openings should not exceed 3 cm/s to 6 cm/s in order to keep the sand movement and head losses to a minimum for a longer life of the well.

V.5 SCREEN MATERIAL

The selection of the screen material depends on the quality of groundwater. Incrustation and corrosion are the usual causes of well failures. The former chemical character plugs the screen openings by deposition of calcium carbonate, thereby reducing the specific capacity of wells, while the latter chemical character enlarges the screen openings by eating the metals, resulting in undesirable quantities of sand entering the well. If the water quality has corrosive or incrusting character (Table V.3), a bimetallic screen should not be used. Therefore, the recommended screen material for various water qualities is shown in Table V.4.

TABLE V.3 Water Quality

Parameters	*Incrustation*	*Corrosion*
pH	> 7	< 7
EC (mho)	–	> 1,500
TDS (mg/l)	–	> 1,000
TA (mg/l)	> 300	> 7
TH (mg/l)	> 300	–
HCO_3^- (mg/l)	> 400	–
Cl^- (mg/l)	–	> 500
SO_4^{2-} (mg/l)	> 100	–
Si (mg/l)	> 40	–
Fe (mg/l)	> 2	–
Mn (mg/l)	> 1	–
CO_2 (mg/l)	–	> 50
DO (mg/l)	–	> 2
H_2S (mg/l)	–	> 1

TABLE V.4 Recommended Screen Material for Various Water Qualities

	Water quality	*Material*	*Analysis*
(a)	Very high TDS (NaCl) with DO (dissolved oxygen)	Monel	70% nickel and 30% copper
(b)	Same as (a), but not quite corrosion- resistant	Super nickel	70% nickel and 30% copper

(c)	High TH, NaCl (without DO), Fe; highly resistant to acid treatment; used for municipal and industrial wells	Everdur silicon-bronze	96% copper, 3% silicon and 1% Manganese
(d)	H_2S, DO, CO_2; Fe-bacteria; used for municipal and industrial wells	Stainless steel	74% steel, 18% chromium and 8% nickel
(e)	Same as (c), but not quite good; used in relatively inactive waters	Silicon red brass	83% copper, 16% zinc and 1% silicon
(f)	Not corrosion-resistant; used for irrigation wells	Armco iron	99.84% pure iron
(g)	Non-corrosion and non-incrustation water	Steel	99.38/99.72% iron, 0.08/15% carbon, 0.20/0.50% manganese

Head loss due to friction in steel pipes is shown in Table V.5, discharge through 90° and 60° V-notches is presented in Table V.6 and discharge through orifices is shown in Table V.7.

TABLE V.5 Head Loss Due to Friction in Steel Pipes (Metres Per 100 Metres of Pipe Length)

Discharge (lpm)	*Diameter of pipe* (mm)			
	25	50	100	200
20	3.71			
40	12.99			
60	27.00	1.15		
80	48.00	2.10		
100	72.01	3.08		
200		11.81		
400		39.01	1.35	
600		79.99	2.79	
800			4.99	
1,000			7.41	
2,000			27.99	0.98
4,000			96.00	3.31
6,000				6.59
8,000				11.52
10,000				17.49

TABLE V.6 Discharge through 90^{o} and 60^{o} V-notches

Head (cm)	*Flow* (l/min)		*Head* (cm)	*Flow* (l/min)	
	90° notch	60° notch		90° notch	60° notch
01	< 1	< 1	24	2,286	1,321
02	5	3	26	2,792	1,613

03	13	7	28	3,360	1,942
04	26	15	30	3,993	2,307
05	45	26	32	4,692	2,711
06	71	41	34	5,460	3,155
07	108	61	36	6,299	3,639
08	147	85	38	7,210	4,166
09	197	114	40	8,197	4,736
10	256	148	42	10,260	5,350
12	404	233	44	10,402	6,010
14	594	343	46	11,625	6,716
16	829	479	48	12,929	7,470
18	1,113	643	50	14,319	8,273
20	1,449	837	55	18,172	10,499
22	1,839	1,062	60	22,587	13,050

TABLE V.7 Discharge through Orifices

Manometer head (cm)	*Orifice diameter* (cm)								
	7.5		10		12.5		15		20
	Pipe diameter (cm)								
	10	15	15	20	15	20	20	25	25
	Discharge (l/min)								
05	216	174	336	306	654	510	858	720	1,590
10	306	240	474	432	924	720	1,218	1,020	2,250
15	372	294	582	528	1,134	882	1,488	1,248	2,754
20	432	342	672	612	1,308	1,020	1,722	1,440	3,180
25	480	384	750	684	1,464	1,140	1,926	1,614	3,558
30	528	420	822	744	1,602	1,248	2,106	1,764	3,900
35	570	456	888	804	1,728	1,344	2,274	1,908	4,212
40	606	486	948	864	1,848	1,440	2,430	2,040	4,500
45	648	516	1,008	912	1,962	1,524	2,580	2,160	4,776
50	678	540	1,062	966	2,070	1,608	2,718	2,280	5,034
55	714	570	1,116	1,008	2,166	1,686	2,850	2,388	5,280
60	744	594	1,164	1,056	2,262	1,764	2,992	2,496	5,514

65	774	618	1,212	1,098	2,358	1,836	3,102	2,598	5,736
70	804	642	1,254	1,140	2,448	1,902	3,216	2,694	5,952
75	834	666	1,302	1,182	2,532	1,968	3,330	2,790	6,162
80	858	684	1,344	1,218	2,616	2,034	3,438	2,880	6,366
85	888	708	1,386	1,254	2,694	2,094	3,546	2,970	6,558
90	912	726	1,422	1,296	2,772	2,160	3,648	3,060	6,750
95	936	750	1,464	1,326	2,850	2,214	3,750	3,144	6,936
100	960	768	1,500	1,362	2,922	2,274	3,846	3,222	7,116

Appendix VI

Geoelectrical Method for Groundwater Exploration

Groundwater, through the various dissolved salts it contains, is ionically conductive and enables electric currents to flow into the ground. Consequently, measuring the ground resistivity
gives the possibility to identify the presence of water, taking in consideration the following properties:

a. A hard rock without pores or fracture and a dry sand without water or clay are very resistive.
b. A porous or fractured rock bearing free water has a resistivity, which depends on the resistivity of water and the porosity of rock.
c. An impermeable clay layer, which has bound water, has a low resistivity.
d. Mineral ore bodies (iron, sulphides, etc.) have very low resistivity due to their electronic conduction, usually lower or much lower than 1 ohm.

VI.1 PROFILING AND VERTICAL ELECTRICAL SOUNDING

In a resistivity profiling, four electrodes spacing are constant and apparent resistivity values are measured at selected stations by shifting the whole electrode array along a profile [Figure VI.1(a) and (b)]. In a vertical electrical sounding (VES), keeping the place of observation constant, a set of apparent resistivity values is obtained successively for different electrode spacing [Figure VI.1(c) and (d)]. Thus, increasing progressively, the distance between the transmitting and the receiving electrodes permits to increase the depth of investigation (vertical electrical sounding array), and translating the four electrodes together permits to detect lateral change of resistivity (profiling array).

The value of apparent resistivity is plotted as a function of electrode spacing on double-log paper. This data can be matched with type (master) curves for obtaining true resistivity (ρ) of the formation.

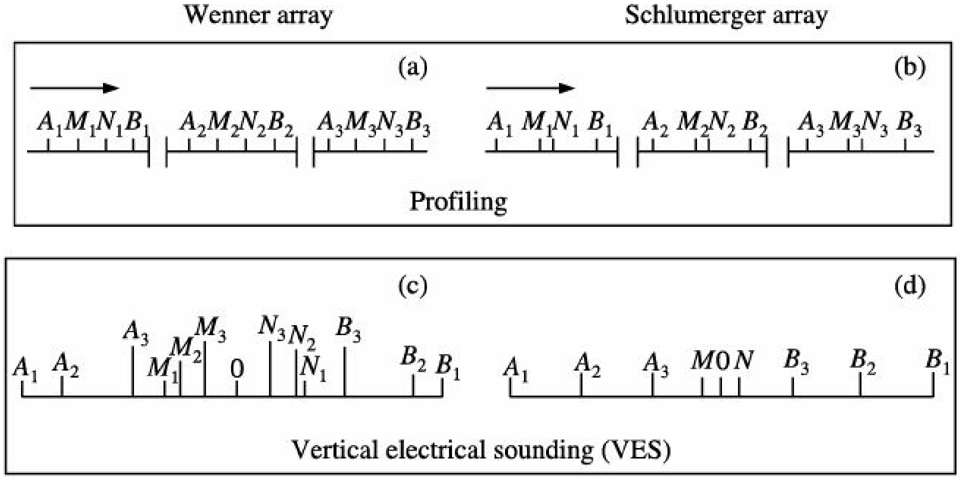


FIGURE VI.1 Electrode arrangement in Wenner and Schlumberger methods for profiling and vertical electrical sounding (VES).

For the three-layer sounding curves in Schlumberger array, the master (type) curves are divided into four groups, depending on the relative values of ρ_1, ρ_2 and ρ_3 (Figure VI.2):

(a) *H*-type: It represents ρ_1, which is more than ρ_2 and less than ρ_3 ($\rho_1 > \rho_2 < \rho_3$), in which resistivity shows high-low-high.

(b) *A*-type: It represents ρ_1, which is less than ρ_2 and ρ_3 ($\rho_1 < \rho_2 < \rho_3$), in which resistivity shows low-low-high.

(c) *K*-type: It represents ρ_1, which is less than ρ_2 and more than ρ_3 ($\rho_1 < \rho_2 > \rho_3$), in which resistivity shows low-high-low.

(d) *Q*-type: It represents ρ_1, which is more than ρ_2 and ρ_3 ($\rho_1 > \rho_2 > \rho_3$), in which resistivity shows high-low-low.

Orellana and Mooney (1966) present master tables and curves, which are widely used, representing 76 three-layer sets (25 each of *H*-type and *K*-type and 13 each of *Q*-type and *A*-type), with a total of 912 three-layer cases.

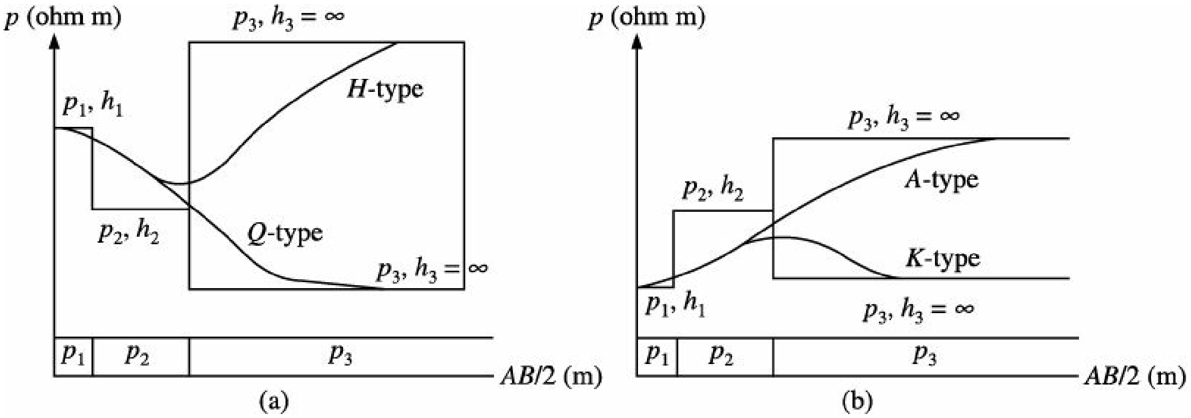


FIGURE VII.2 (a) *H*-type and *Q*-type, and (b) *A*-type and *K*-type for three-layer type curves in Schlumberger configuration.

General range of electrical resistivity of common rocks is shown in Table VI.1.

TABLE VI.1 General Range of Electrical Resistivity of Common Rocks with Water

Geological formations	*Resistivity* (Ohm m)
Deccan basalts	
Black cotton soil and bole bed	5–10
Weathered or fractured vesicular basalt saturated with water	20–45
Moderately weathered or fractured basalt or vesicular basalt saturated with water	40–70
Hard and massive basalt	> 70
Granites	
Highly weathered granite	20–50
Semi weathered granite	50–120
Fractured or jointed granite	120–200
Massive granite	> 300
Sandstones	
Water saturated or highly weathered sandstones	< 50
Fractured sandstones	50–300
Hard and compact sandstones	>300
Alluvium	
Clay	< 10
Sand with clay	10–20
Sand	20–50
Water	
Surface water (freshwater lakes, rivers etc.)	300–500
Potable groundwater	10–100

Saline water	
1% NaCl	0.75
5% NaCl	0.15
10% NaCl	0.08
Mine water	0.30

Appendix VII

Groundwater Quality

Some cations and anions are shown in Table VII.1, some conversion factors from mg/l to meq/l and from mg/l to mmol/l are given in Table VII.2 and recommended distance between groundwater well and sources of contamination is presented in Table VII.3

TABLE VII.1 Cations and Anions

Cations		*Anions*	
Calcium	Alkaline earths	Bicarbonate	Weak acids
Magnesium		Carbonate	
Sodium	Alkalis	Chloride	Strong acids
Potassium		Sulphate	
		Nitrate	
		Fluoride	

TABLE VII.2 Conversion Factors

Element/Ion	F_1	F_2	*Element/Ion*	F_1	F_2
Aluminium (Al^{3+})	0.11119	0.03715	Lead (Pb)	–	0.00483
Ammonium NH_4^+	0.05544	0.05544	Lithium (Li$^+$)	0.14411	0.14411
Barium (Ba^{2+})	0.01456	0.00728	Magnesium (Mg^{2+})	0.08226	0.04113
Beryllium (Be^{3+})	0.33288	0.11096	Manganese (Mn^{2+})	0.03640	0.01820
Bicarbonate HCO_3^-	0.01639	0.01639	Molybdenum (Mo)	–	0.01042
Boron (B)	–	0.09250	Nickel (Ni)	–	0.01703
Bromide (Br$^-$)	0.01251	0.01251	Nitrate (NO_3^-)	0.01613	0.01613
Cadmium (Cd^{2+})	0.01779	0.00890	Nitrite (NO_2^-)	0.02174	0.02174
Calcium (Ca^{2+})	0.04990	0.02495	Phosphate (PO_4^{3-})	0.03159	0.01053
Carbonate CO_3^{2-}	0.03333	0.01666	Phosphate (HPO_4^-)	0.02084	0.01042
Chloride (Cl$^-$)	0.02821	0.02821	Phosphate ($H_2PO_4^-$)	0.01031	0.01031
Chromium (Cr)	–	0.01923	Potassium (K$^+$)	0.02557	0.02557
Cobalt (CO^{2+})	0.03394	0.01697	Rubidium (Rb$^+$)	0.01170	0.01170

Copper (Cu^{2+})	0.03148	0.01574	Silica (SiO_2)	–	0.01664
Fluoride (F^-)	0.05264	0.05264	Silver (Ag)	–	0.00927
Germanium (Ge)	–	0.01378	Sodium (Na^+)	0.04350	0.04350
Gallium (Ga)	–	0.01434	Strontium (Sr^{2+})	0.02283	0.01141
Gold (Au)	–	0.00511	Sulphate SO_4^{2-}	0.02082	0.01041
Hydrogen (H^+)	0.99209	0.99209	Sulphide (S^{2-})	0.06238	0.03119
Hydroxide (OH^-)	0.05880	0.05880	Titanium (Ti)	–	0.02088
Iodide (I^-)	0.00788	0.00788	Uranium (U)	–	0.00420
Iron (Fe^{2+})	0.03581	0.01791	Zinc (Zn^{2+})	0.03060	0.01530
Iron (Fe^{3+})	0.05372	0.01791			

Note: F_1: Conversion from milligrams per litre (mg/l) to milliequivalents per litre (meq/l)
F_2: Conversion from mg/l to millimoles per litre (mmol/l)

VII.1 CHARACTERISTICS OF GROUNDWATER QUALITY

Aluminium

Aluminium (Al) is derived from bauxite and other clays. Although present in many rocks, aluminium is not highly soluble and precipitates readily**.** There is no evidence that it affects the use of water for most purposes. Acid water (low pH) often contains great amount of aluminium. Such water is troublesome for boiler feed because of the formation of scale.

Silica

Dissolved from practically all rocks and soils, silica (SiO_2) is generally found in small amounts from 1 mg/l to 30 mg/l. Higher concentrations generally occur in highly alkaline water. Silica forms a hard scale in pipes and boilers. Carried over in steam of high-pressure boilers, silica forms damaging deposits on the delicately balanced blades of steam turbines. Silica also inhibits the deterioration of zeolite-type water softeners, but does not affect water for domestic purposes. Groundwater generally contains more silica than surface water.

Iron

Extremely common, iron (Fe) is dissolved from practically all rocks and soils. Water having a low pH tends to be corrosive and may dissolve iron in objectionable quantities from pipe, pumps, and other equipment. More than 1 mg/l to 2 mg/l of soluble iron in surface water generally indicates the presence of acid wastes from mine drainage or other sources. More than about 0.3 mg/l iron stains laundry and utensils reddish-brown. Objectionable for food processing, beverages, dyeing, bleaching, ice manufacturing, brewing, and other processes, moderately large quantities cause unpleasant taste and favour the growth of iron bacteria under slight oxidising conditions and typical groundwater temperatures. On exposure to air, iron in groundwater is readily oxidised and forms a reddish-brown precipitate. Iron can be removed by oxidation, sedimentation and fine filtration, or by precipitation during removal of hardness by ion exchange (not a recommended practice).

Manganese

Dissolved from some rocks and soils, and not so common as iron, manganese has many of the same objectionable features as iron. The oxidised form of manganese causes dark brown or black stains. Large quantities of manganese are commonly associated with high iron content and acid water.

Biochemical oxygen demand (BOD)

Biochemical oxygen demand (*BOD*) is the amount of dissolved oxygen needed by aerobic biological organisms in a water body to break down organic material present in a given water sample at certain temperature over a specific time period. The BOD is most commonly expressed in milligrams of oxygen consumed per litre of sample during 5 days of incubation at 20 °C and is often used as a robust surrogate of the degree of organic pollution of water.

Chemical oxygen demand (COD)

Chemical oxygen demand (*COD*) is an indirect measurement of the amount of organic compounds in water. Most of the applications of the COD determine the amount of organic pollutants found in surface water (e.g., lakes and rivers) or waste water, making COD a useful measure of water quality. It is expressed in milligrams per litre (mg/l), which indicates the mass of oxygen consumed per litre of solution.

Dissolved oxygen (DO)

Dissolved oxygen (*DO*) refers to the level of free, non-compound oxygen present in water. It is an important parameter in assessing water quality because of its influence on the organisms living within a water body. It is measured in milligrams per litre (mg/l), or the number of milligrams of oxygen dissolved in a litre of water. A dissolved oxygen level that is too high or too low can harm aquatic life and affect water quality.

Radiological prosperities of groundwater quality

Radionuclides in water are classified according to the type of energy released. They are alpha radiation (positively charged helium nuclei), beta radiation (electrons) and gamma radiation (electromagnetic energy). Natural radiation is found in the elements present in the Earth's crust [potassium-40 (^{40}K)]. Another source of natural radiation results from cosmic ray bombardment in the atmosphere [tritium (^{3}H) and carbon-14 (^{14}C)]. Other high-atomic weight, naturally occurring isotopes found in natural water include uranium-238, thorium-232, uranium-235 and breakdown products as radium-226 and radium-228. The units of radiation measurements are curies (Ci) or rems (Ci = 3.7×10^{10} nuclear transformations per second; picocurie (pCi) = 10^{-12} Ci). A rem is the radiation dose producing the same biological effect (rem = Absorbed dose × Quality factors).

Each type of radiation has different health effects. For example, alpha particles travel at 10^{7} m/s velocities. When ingested, the relatively massive alpha particles can be very damaging to body tissue. Beta particles travel at about the speed of light, penetrate to greater depth because of their smaller mass and create less damage. Gamma radiation penetrates deeply, but has limited effects at low levels. The body dose that accurses from drinking water compared to natural background radiation is low, however, the EPA policy assumes that potential harm exists from any level of radiation.

Dissolved gases

The principal transfer of gas in natural water is the transfer of oxygen from atmosphere to water. However, gas transfer is also used to strip hydrogen sulphide (H_2S), ammonia (NH_3) and volatile organic compounds (VOCs) from water. In both processes, material is transferred from one bulk phase to another across a gas-liquid interface. For example, oxygen is transferred from the bulk gaseous phase (atmosphere) across the gas-liquid interface into bulk liquid phase (water). In the case of striping a volatile organic compound (VOC) from liquid, the VOC is transferred from the bulk liquid phase (water) across the liquid-gas interface into the bulk gaseous phase (atmosphere).

Microorganisms

Many bacteria, viruses and protozoa are causative organisms for some of the more virulent diseases transmitted to humans directly through water and indirectly through contaminated food. Assay and confirmation of the presence of the causative agent of waterborne diseases are lengthy and time-consuming. Instead of specific analyses, coliform organisms have been used to determine the biological characteristics of natural water. The coliform bacteria are aerobic and/or facultative gram-negative, non-spore forming and rod-shaped that ferment lactose to gas. *Escherichia coli* is commonly used as an indicator organism. This organism is present in the intestine of warm-blooded animals, including humans. Therefore, the presence of *Escherichia coli* in water samples indicates the presence of fecal matter, and then, the possible presence of pathogenic organisms of human origin. The concentration of indicator organisms is reported in MPN/100 ml (MPN is most probable number). Other enteric organisms that are also considered as indicator organisms are fecal streptococci (*Streptococcus faecalis*) and clostridia (*Clostridium perfringens*).

TABLE VII.3 Recommended Distance between a Groundwater Well and Sources of Contamination

Contamination source	*Recommended distance* (m)
Building sewer	15
Septic tank	15
Disposal field	30
Seepage pit	30
Cess pool	45

Appendix VIII

Quality Criteria for Water Use

VIII.1 DRINKING PURPOSE

In general, the quality of water is extremely high. However, industrial, agricultural and urban development has had varying effects on the quality of water bodies present in all the regions. Generally, water quality declines from mountains to sea, reflecting the increasing intensity of land use near the coast, changes in catchment geology, and accumulation of contaminants.

Water quality standards for drinking have been developed by World Health Organisation (WHO, 2011) and Bureau of Indian Standards (BIS, 2012; Table VIII.1). Quality criteria are generally based on water intake per person per day. Drinking water should be unpolluted. Otherwise, it causes health disorders.

TABLE VIII.1 Suitability of Water Quality for Drinking Purpose

Chemical variables	*BIS* (2012)		*WHO* (2011)	
	HDL	*MPL*	*Acceptable*	*Allowable*
Colour (HU)	5	15	5	15
Odour	Agreeable		Agreeable	
Turbidity (JTH)	1	5	1	5
Taste	Agreeable		Agreeable	
pH	6.5 to 8.5	–	6.5 to 8.5	–
TDS (mg/l)	500	2,000	500	1,500
TA (mg/l)	200	600	–	–
TH (mg/l)	200	600	200	600
Ca^{2+} (mg/l)	75	200	75	200
Mg^{2+} (mg/l)	30	100	30	100
Na^{+} (mg/l)	200	–	200	–
Cl^{-}(mg/l)	250	1,000	250	1,000
SO$_4^{2-}$ (mg/l)	200	400	500	–
NO$_3^{-}$ (mg/l)	45	–	50	–

F^- (mg/l)	1.0	1.5	1.5	–
Fe (mg/l)	0.3	–	0.3	–
Ba (mg/l)	0.7	–	0.7	–
Cu (mg/l)	0.05	1.5	2.0	–
Mn (mg/l)	0.1	0.3	0.4	–
Cd (mg/l)	0.003	–	0.003	–
CN (mg/l)	0.05	–	0.05	–
Pb (mg/l)	0.01	–	0.01	–
Hg (mg/l)	0.001	–	0.006	–
Mo (mg/l)	0.07	–	0.07	–
Ni (mg/l)	0.02	–	0.07	–
Ar (mg/l)	0.01	0.05	0.01	–
Cr (mg/l)	0.05	–	0.05	–
Se (mg/l)	0.01	–	0.04	–
Ag (mg/l)	0.1	–	0.1	–
Zn (mg/l)	0.3	–	–	–
Alpha emitters (bq/l)	0.1	–	–	–
Beta emitters (bq/l)	1.0	–	–	–
E. coliform bacteria	Shall not be detectable		Shall not be detectable	

Note: HDL stands for highest desirable limit, and MPL stands for maximum permissible limit.

VIII.2 IRRIGATION PURPOSE

Excessive concentrations of dissolved ions in the irrigation water affect plants and agricultural soil physically and chemically by lowering the osmotic pressure in the plant structural cells. This prevents water from reaching the branches and leaves, thus reducing the agricultural productivity.

Salinity hazard versus sodium hazard

For assessment of water quality for irrigation, salinity hazard, sodium hazard, per cent sodium, permeability index, residual sodium carbonate and magnesium ratio are widely used.

Suitability of water for irrigation mainly depends on relative concentrations of salinity (EC) and Na^+ in relation to other cations and anions. Salinity hazard (C) indicates leaching of salts into water, which creates a lot of problems, especially in dry climatic regions, where the clayey soils occur. The saline water develops saline soil, which affects salt intake capacity of plants through roots. Excess salts in agricultural fields caused by water loss through evaporation develop poor drainage conditions. These conditions decline water levels up to root zone of plants, which accumulates salts in soil solution through capillary rise, following water evaporation. On the other hand, if Na^+ combines with carbonates, it forms alkaline soils, and if it combines with Cl^-, it develops saline soils. Sodium adsorbed on clay surfaces by substituting alkaline earths destroys a soil structure. It makes soil compact and impervious, and hence, plant growth reduces. Sodium hazard (S) is a tendency of water to replace adsorbed Ca^{2+} plus Mg^{2+} with Na^+, which is expressed in terms of sodium adsorption ratio (SAR). This is a ratio of Na^+ concentration to the square root of half of the combination of Ca^{2+} and Mg^{2+} concentration. Another expression of sodium hazard is percent sodium (%Na^+). This is a ratio of the combination of Na^+ and K^+ concentration to the combination of Ca^{2+}, Mg^{2+}, Na^+, and K^+ concentration, which is multiplied by 100. Table VIII.2 shows the classification of salinity hazard and sodium hazard.

TABLE VIII.2 Classification of Salinity Hazard and Sodium Hazard

Zone	*Description*	*Zone*	*Description*
*C*1	Low-salinity (EC: < 250 μS/cm) water can be used for irrigation of most crops on most soils, with little likelihood of soil salinity development. Some leaching is required, but this occurs under normal irrigation practices, except in soils of extremely low permeability.	*S*1	Low-sodium (SAR: < 10) water can be used for irrigation on almost all soils, with little danger of the development of harmful levels of exchangeable sodium.
*C*2	Medium-salinity (EC: 250 μS/cm to 750 μS/cm) water can be used if a moderate amount of leaching occurs. Crops of moderate salt tolerance (Table VIII.3) can be irrigated with this water without special practices for salinity control.	*S*2	Medium-sodium (SAR: 10 to 18) water will be present an appreciate sodium hazard in fine-textured soils, especially poorly leached soils. Such water may be used safely on coarse textured or organic soils that have good permeability.
*C*3	High-salinity (EC: 750 μS/cm to 2,250 μS/cm) water cannot be used on soils of restricted drainage. Even with adequate drainage, special management for salinity control may be required and crops of good salt tolerance can be selected (Table VIII.3).	*S*3	High-sodium (SAR: 18 to 26) water may produce harmful levels of exchangeable sodium in most soils. It requires a special soil management like good drainage, high leaching and addition of organic matter.
*C*4	Very high-salinity (EC: > 2,250 μS/cm) water is not suitable for irrigation under ordinary conditions. It can be used only on crops that are very tolerant of salt (Table VIII.3) and only if special practices are followed, including provision for a high degree of adverse effects.	*S*4	Very high-sodium (SAR: > 26) water is generally unsatisfactory for irrigation, unless special action is taken, for example, addition of gypsum to the soil.

TABLE VIII.3 Relative Tolerance of Crops to Salt Concentration

Sensitive	*Semi-tolerant*	*Tolerant*

Apricot	Alfalfa	Spinach
Arhar	Apple	Barely
Beans	Banana	Beets
Grams	Cabbage	Cotton
Grape fruit	Carrot	Sugar beet
Lemon	Grapes	Sugarcane
Moong	Guava	Sarson
Orange	Jowar	Tobacco
Peas	Karela	
Plum	Lemon	
Walnut	Maize	
	Mango	
	Olive	
	Onion	
	Orange	
	Pear	
	Potato	
	Rice	
	Sunflower	
	Tomato	
	Wheat	

Appendix IX

Chemical Activities

The relation of activity coefficients for dissolved ions to the ionic strength of solution is shown in Figure IX.1 below:

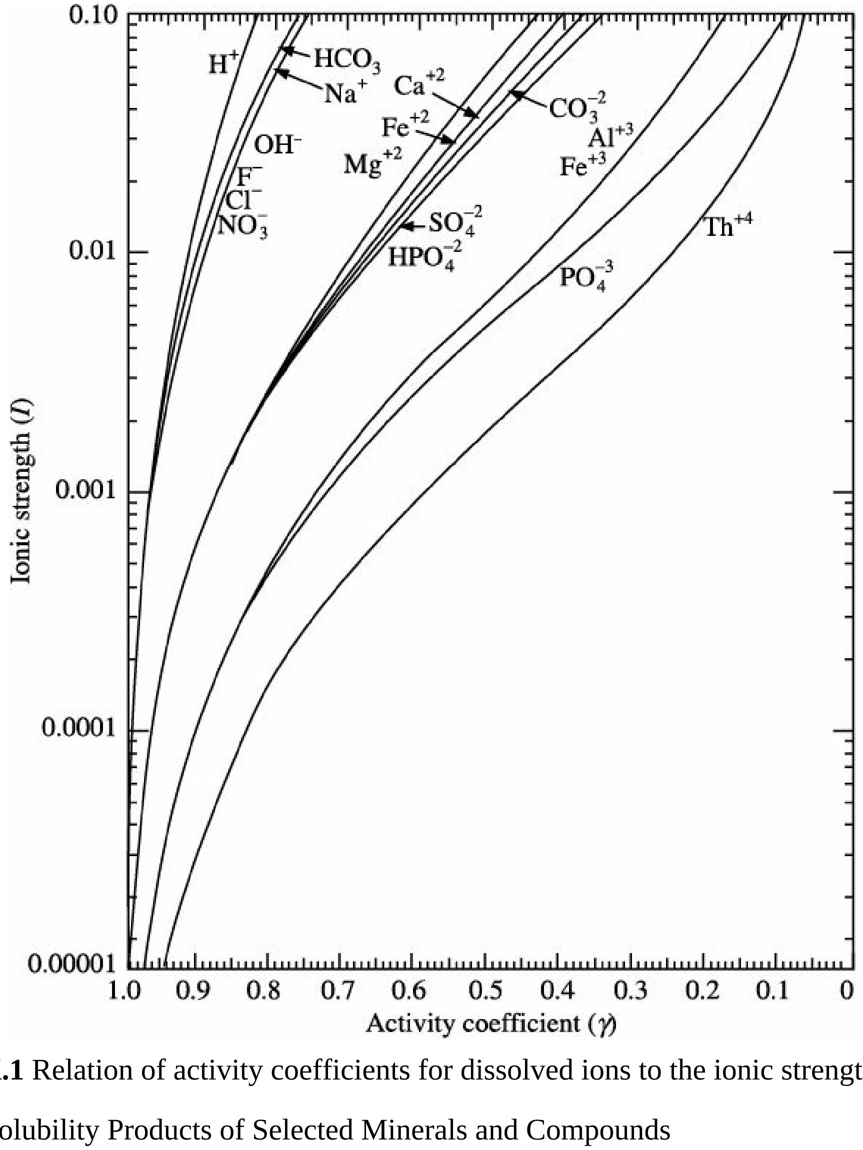


FIGURE IX.1 Relation of activity coefficients for dissolved ions to the ionic strength of solution.

TABLE IX.1 Solubility Products of Selected Minerals and Compounds

Compound	*Solubility*	*Mineral name*	*Compound*	*Solubility*	*Mineral name*
Sulphides			***Carbonates***		
CdS	$10^{-28.2}$		$BaCO_3$	$10^{-8.3}$	Witherite

Cu_2S	$10^{-48.5}$	Chalcocite	$CdCO_3$	$10^{-13.7}$	Otavite
CuS	$10^{-36.1}$	Covellite	$CaCO_3$	$10^{-8.35}$	Calcite
FeS	$10^{-18.1}$	Phyrrhotite	$CaCO_3$	$10^{-8.22}$	Aragonite
FeS_2	$10^{-26.1}$	Pyrite	$CaMg\ (CO_3)_2$	$10^{-17.0}$	Dolomite
MnS	$10^{-12.8}$	Crystalline	$CoCO_3$	$10^{-10.0}$	Cobalt
MnS	$10^{-15.7}$	Precipitated	$FeCO_3$	$10^{-10.7}$	Siderite
PbS	$10^{-27.5}$	Galena	$PbCO_3$	$10^{-13.1}$	Cerussite
HgS	$10^{-55.3}$	Cinnabar	$MgCO_3$	$10^{-7.5}$	Magnesite
ZnS	$10^{-22.5}$	Wurtzite	$MnCO_3$	$10^{-9.3}$	Rhodochrosite
ZnS	$10^{-24.7}$	Sphalerite	$SeCO_3$	$10^{-11.8}$	Strontianite
Fluorides			***Chlorides***		
BaF_2	$10^{-5.8}$		CuCl	$10^{-6.7}$	
CaF_2	$10^{-10.4}$	Fluorite	$PbCl_2$	$10^{-4.8}$	
MgF_2	$10^{-8.2}$	Sellaite	Hg_2Cl_2	$10^{-17.9}$	
PbF_2	$10^{-7.5}$	Fluorocronite	AgCl	$10^{-9.7}$	
SrF_2	$10^{-8.5}$		NaCl	$10^{-1.60}$	Halite
Sulphates			***Phosphates***		
$BaSO_4$	$10^{-10.0}$	Barite	$AlPO_4.2H_2O$	$10^{-22.1}$	Variscite
$CaSO_4$	$10^{-4.5}$	Anhydrite	$CaHPO_4.2H_2O$	$10^{-6.6}$	
$CaSO_4.2H_2O$	$10^{-4.6}$	Gypsum	$Ca_3(PO_4)_2$	$10^{-28.7}$	
$PbSO_4$	$10^{-7,8}$	Anglesite	$Cu_3(PO_4)_2$	$10^{-36.9}$	
Ag_2SO_4	$10^{-4,8}$		$FePO_4$	$10^{-21.6}$	
$SrSO_4$	$10^{-6.5}$	Celesite	$FePO_4.2H_2O$	$10^{-26.4}$	
Oxides and hydroxides					
$Al(OH)_3$	$10^{-32.8}$	Gibbsite			
$Fe(OH)_3$	$10^{-37.1}$	Amorphous			
α–FeOH	$10^{-41.2}$	Goethite			
α-MnO_2	$10^{-15.9}$	Pyrolusite			

Appendix X

Logarithms and Anti-Logarithms

TABLE X.1 Logarithms

N	0	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529
18	2553	2577	2601	2625	2648	.2672	2695	2718	2742	2765
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899

39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802

76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996

TABLE X.2 Anti-logarithms

N	0	1	2	3	4	5	6	7	8	9
.00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021
.10	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045
.02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069
.03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094
.04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119
.05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146
.06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172
.07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199
.08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227
.09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256
.10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285

.11	1228	1291	1294	1297	1300	1303	1306	1309	1312	1315
.12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346
.13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377
.14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409
.15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442
.16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476
.17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510
.18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545
.19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581
.20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618
.21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656
.22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694
.23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734
.24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774
.25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816
.26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858
.27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901
.28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945
.29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991
.30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037
.31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084
.32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133
.33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183
.34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234
.35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286
.36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339
.37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393
.38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449
.39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506
.40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564
.41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624
.42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685
.43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748
.44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812
.45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877
.46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944
.47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013

.48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083
.49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155
.50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228
.51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304
.52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381
.53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459
.54	3467	3475	3483	3491	3499	3508	3516	3524	3522	3540
.55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622
.56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707
.57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793
.58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882
.59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972
.60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064
.61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159
.62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256
.63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355
.64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457
.65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560
.66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667
.67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775
.68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887
.69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000
.70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117
.71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236
.72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358
.73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483
.74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610
.75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741
.76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875
.77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012
.78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152
.79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295
.80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442
.81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592
.82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745
.83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902
.84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063

.85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228
.86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396
.87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568
.88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745
.89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925
.90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110
.91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299
.92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492
.93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690
.94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892
.95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099
.96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311
.97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528
.98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750
.99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977

Appendix XI

Miscellaneous Conversions

TABLE XI.1 Length

Unit	*Equivalent of first column*					
	Centimetres	*Metres*	*Kilometres*	*Inches*	*Feet*	*Mile*
1 cm	1	0.01	0.00001	0.3937	0.0328	0,0000062
1 m	100	1	0.001	39.37	3.2808	0.000621
1 km	100,000	1,000	1	39,370	3,280.8	0.621
1 inch	2.54	0.0254	0.0000254	1	0.0833	0.000016
1 ft	30.48	0.3048	0.000305	12	1	0.000189
1 mile	160,935	1,609.3	1.6093	63,360	5,280	1

TABLE XI.2 Area

Unit	*Equivalent of first column*					
	Square metres	*Square feet*	*Acres*	*Hectares*	*Square miles*	*Square kilometres*
1 m^2	1	10.76	0.000247	0.00001	–	0.000001
1 ft^2	0.0929	1	0.000023	0.0000093	–	0.000011
1 acre	4,047	43,560	1	0.4047	0.00156	0.004
1 ha	10,000	107,639	2.471	1	0.00386	0.01
1 mile^2	2,589,998	27,878,400	640	259	1	2.59
1 km^2	1,000,000	10,763,869	247.1	100	0.386	1

Note: 1 hectare metre is equal to 8.10 acre feet; 1 acre foot is equal to 0.123 hectare metre.

TABLE XI.3 Volume

Unit	*Equivalent of first column*				
	Cubic metre	*Litre*	*US gallon*	*Imperial gallon*	*Cubic feet*
1 m^3	1	1,000	264.17	220.08	35.31
1 l	0.001	1	0.264	0.220	0.0353
1 US gal	0.00379	3.785	1	0.833	0.134

1 Imperial gal	0.00454	4.542	1.2	1	0.160
1 cubic foot	0.0283	28.317	7.48	6.232	1

TABLE XI.4 Flow

Unit	*Equivalent of first column*				
	Cubic feet per second	*US gallons per minute*	*Imperial gallon per minute*	*Litre per second*	*Cubic metre per hour*
1 ft^3/s	1	448.83	374.03	28.317	101.94
1 US gal/min	0.00223	1	0.833	0.0631	0.2271
1 Imperial gal/min	0.00267	1.2	1	0.0758	0.2728
1 l/s	0.03531	15.847	13.201	1	3.6
1 m^3/hour	0.00981	4.4028	3.666	0.2778	1

TABLE XI.5 Miscellaneous

Particulars		
Acceleration due to gravity, g		981 cm/s^2 or 9.807 m/s^2
Water density, ρ		1,000 km/m^3
Water specific weight, γ		0.1 $kg/cm^2/m$
Force	1 kgf	9.81 N
Power	1 m kgf/sec	9.81 Nm/s (W)
	1 metric hp	736 W or 0.736 kW
Dynamic viscosity, μ	1 kgf - s/m^2	9.81 N s/m^2 or 98.1 poise
	1 N s/m^2	10 poise or 1,000 centipoise
Kinematic viscosity, v	1 m^2/s	10^4 stokes or 10^6 centistokes
Temperature	°F	$\frac{9}{5}(°C)+32$
	°C	$\frac{5}{9}(°F-32)$

TABLE XI.6 Common Map Scales

Scale of map	*Reduction factor (RF)*	*Approximate metric scale*
1 inch = 16 miles	1 : 1,013,760	1 cm = 10 km
1 inch = 4 miles	1 : 253,440	1 cm = 2.5 km
1 inch = 2 miles	1 : 126,720	1 cm = 1.25 km
1 inch = 1 mile	1 : 63,360	1 cm = 500 m

TABLE XI.7 Scale and Contour Interval

Scale	*Contour interval*

1 cm = 6 m	30 cm
1 cm = 12 m	60 cm
1 cm = 25 m	1.5 m
1 cm = 60 m	3 m

TABLE XI.8 Slopes, Gradients and Dips

Ratio	*Percent*	*Angle θ*	*tan θ*	*sin θ*
1 : 0 vertical	–	90	–	1
1 : 1	100	45	1.0000	0.7071
1 : 2	50	26°34′	0.5000	0.4472
1 : 3	33	18°26′6″	0.3333	0.3162
1 : 5	20	11°18′35″	0.2000	0.1961
1 : 10	10	5°42′36″	0.1000	0.0995
1 : 50	2	1°8′45″	0.0200	0.0200
1 : 100	1	0°34′23″	0.0100	0.0100
1 : 200	0.50	0°17′11″	0.0050	0.0050
1 : 300	0.33	0°11′28″	0.0033	0.0033
1 : 400	0.25	0°8′36″	0.0025	0.0025
1 : 500	0.20	0°6′53″	0.0020	0.0020
1 : 1,000	0.10	0°3′26″	0.0010	0.0010
1 : 2,000	0.05	0°1′43″	0.0005	0.0005
1 : 5,000	0.02	0°0′41″	0.0002	0.0002

Appendix XII

Frequently Used Symbols

TABLE XII.1 Frequently used Symbols

Symbol	*Dimension*	*Unit*	*Explanation*
A, a	L^2	m^2	Area
B	L	m	Drainage factor of an unconfined aquifer with delayed yield = $\sqrt{\frac{kb}{\alpha S_\gamma}}$
b	L	m	Thickness of aquifer
b'	L	m	Thickness of confining layer
Cr	T	day	Hydraulic resistance of semi-pervious layer = $\frac{b'}{k'}$
D	L	m	Diameter of screen or pipe
d	L	mm	Diameter of soil particles
d_{10}	L	mm	Diameter of soil particles of which 10% by weight are finer
E	$ML^{-1}T^{-2}$	kg/m^2	Bulk modulus of elasticity of a liquid
E_s	$ML^{-1}T^2$	kg/m^2	Modulus of vertical compression or elasticity of solid skeleton of an aquifer
e	Dimensionless	–	Void ratio
g	LT^{-2}	m/s^2	Acceleration due to gravity (= 9.81 m/s^2)
h	L	M	Piezometric head
i	Dimensionless	–	Hydraulic gradient
K	LT^{-1}	m/day	Hydraulic conductivity or permeability
k'	LT^{-1}	m/day	Hydraulic conductivity or permeability of a semi-pervious confining layer
k_s	LT^{-1}	m/day	Laboratory hydraulic conductivity or permeability
l	L	m	Length
m	L	m	Hydraulic mean radius (= flow area/wetted perimeter)
n	Dimensionless	–	Porosity
ρ	$ML^{-1}T^{-2}$	kg/cm^2	Pressure (atmospheric pressure taken as datum)
Q	L^3T^{-1}	m^3/day	Discharge
q	L^2T^{-1}	m^2/day	Discharge per unit width
R	L	m	Radius of screen or pipe
r	L	m	Radius
r_o	L	m	Radius of influence of a well

r_w	L	m	Effective radius of well
S	Dimensionless	–	Storage coefficient or storativity or specific yield
S'	Dimensionless	–	Specific yield of a semi-pervious layer
S_γ	Dimensionless	–	Specific yield after a long pumping test
s	L	m	Drawdown
T	L^2T^{-1}	m^2/day	Transmissivity (= kb)
u	LT^{-1}	m/day	Velocity component in x-direction
V	LT^{-1}	m/day	Discharge velocity, average velocity
V	L^3	m^3	Volume
V_v	L^3	m^3	Volume of voids
V_s	L^3	m^3	Volume of solids
v	LT^{-1}	m/day	Velocity component in y-direction
v	LT^{-1}	m/day	Velocity through the interstices of an aquifer
w	LT^{-1}	m/day	Velocity component in z-direction
w'	LT^{-1}	m/day	Recharge or outflow velocity in vertical direction
α	$M^{-1}LT^2$	m^2/kg	Compressibility of laterally confined soils
$\frac{1}{\alpha}$	$ML^{-1}T^{-2}$	kg/m^2	Delay index of Boulton
β	$M^{-1}LT^2$	m^2/kg	Compressibility of a liquid (= I/E)
γ	$ML^{-2}T^{-2}$	kg/m^2	Specific weight of water (= $\rho_w g$)
λ	L	day	Leakage factor (= $\sqrt{kbc}$)
μ	$ML^{-1}T^{-1}$	kg s/m^2	Dynamic viscosity
ν	L^2T^{-1}	m^2/s stokes	Kinematic viscosity
ρ_ω	ML^{-3}	metric slugs/m	Density of water
φ	L^2T^{-1}	–	Velocity potential (= kh)

Notes:

a. Suffixes x, y and z refer to the three coordinate directions.
b. Primes (′) refers to conditions in semi-confining layers.

Appendix XIII

Well-inventory Form

1. Particulars of the area

a. Date of investigation:
b. Name of village/city/town with street and colony:
c. Name of taluka/mandal:
d. Name of district:
e. Name of state:

2. Particulars of well

a. Well/sample number:
b. Reference landmark of well location:
c. Latitudes and longitudes (of well location) with toposheet number:
d. Type of well (dug well/dug-cum-bore well/tube well/borewell):
e. Private/Government well:
f. Name of well owner (if private well):
g. Well measuring point (mp) above the land surface:
h. Total depth of well (m) below mp (bmp):
i. Diameter (inner) of well (m):
j. Measured/reported pre-monsoon depth to water level (m, bmp):
k. Measured/reported post-monsoon depth to water level (m, bmp):

3. Particulars of collection of water sample

a. Time of collection:
b. Air temperature (°C):
c. Water temperature (°C):
d. Colour of water (dirty, turbid, muddy, etc.):
e. Odour of water (odour-free, soapy, aromatic, rotten eggs, etc.):
f. Taste of water (good, brackish, saline, bitter, etc.):

g. Potable water or non-potable water:
h. Field pH and EC (micro-Siemens):

4. Particulars of water drawn

a. Mode of water drawn (bucket/mhote/electric motor):
b. Type of pump (submersible/jet/turbine, etc.) with horsepower:
c. Well discharge per hour (l):
d. Number of working hours of pump per day:

5. Particulars of water use

a. Water use (domestic/irrigation/industry):
b. Command/non-command area of well (acres):
c. Crops grown (kharif/rabi) under well water:

6. Particulars of geological background

a. Topography (local/regional):
b. Geological exposures (local/regional):
c. Soil type (sandy/clayey/silty, etc.) and thickness (m):
d. Observed/reported weathering thickness (m):
e. Observed/reported depth of fractured zones (m):

7. Remarks (well location nearby fractured rock, garbage, drainage wastes, irrigation activity,
industrial effluents, mining activities, etc.):

8. Any other relevant information (well-sections/litho-logs etc.)

Glossary

Activity coefficient: A factor of thermodynamics for deviation from ideal behaviour in a mixture of chemical substances

Actual evapotranspiration: A quantity of water that is actually removed from a surface due to processes of evaporation and transpiration

Actual pH: A measured pH in the field

Alkalies: Sodium and potassium ions

Alkaline earths: Calcium and magnesium ions

Allen Hazen's formula: An empirical formula used for approximating the hydraulic conductivity from grain size analyses

Angular drainage pattern: A drainage pattern, where the bedrock joints and faults intersect at more acute angles than rectangular drainage patterns

Anion: A negatively charged ion, which attracts an anode in electrolysis

Annual draft: A quantity of water withdrawn from the groundwater reservoirs, which is computed by multiplying its average discharge and annual working hours

Annular drainage pattern: A ring-like drainage pattern that is subsequent in origin and associated with maturely dissected dome or basin structures

Annual rainfall: An amount of water falling rain expressed as a depth of coverage

Annual water level fluctuation: A difference of water level between the pre- and post-monsoon

Anthropogenic origin: An origin that describes changes in nature made by people

Apparent resistivity: An Ohm's-law ratio of measured voltage (V) to applied current (I), multiplied by a geometric constant k, which depends on the electrode array ($\rho_a = kV/I$).

Aquiclude: A saturated, but relatively impermeable material that does not yield appreciable quantity of water to wells

Aquifer: A water-bearing formation, which yields sufficient quantity of water to wells due to enough transmitting and storage capacity of water in it

Aquifer loss: Loss of water in aquifer material, arising from laminar flow

Aquifer test: A test for determination of transmissivity and storativity

Aquifuge: A relatively impermeable formation neither containing nor transmitting water

Aquitard: A saturated, but poorly permeable formation that impedes groundwater movement and does not yield water freely to wells, but that may transmit appreciable water to adjacent aquifer

Areal aspects: Two-dimensional landforms

Arid climate: One that receives less than 25.4 cm of rainfall in an entire year

Aridity index: A degree of dryness of the climate at a given location

Artificial gravel pack: A suitable coarse and uniform gravel pack placed around screen not only to improve discharging capacity of well by replacement of finer aquifer material around screen, but also to stabilise fine-grained and poor aquifers

Arithmetic average: A sum of all the numbers in the series divided by the count of all numbers in the series

Average areal depth of rainfall: An estimation by taking simple average of all selected point rainfall values for the area under consideration

Average rate of recharge: The ratio of the average base flow per metre length of drain to the distance between the drains

Barometric efficiency: The ratio of water level change to the atmospheric pressure change in a well

Basin area: The total area projected upon a horizontal plane contributing to cumulate all orders of basins

Basin divide: A line that separates neighbouring drainage basins along topographical ridges

Basin length: A straight line from the mouth of a stream to the farthest point on the drainage divide of its basin

Basin perimeter: A length of boundary of a basin

Basin width: The longest dimension of basin perpendicular to principal drainage line

Bifurcation ratio: The ratio of a number of stream branches of a given order to the number of stream branches of the next higher order

Border strip of irrigation: A system of surface irrigation in which water flows and spreads over sloping strips of land between two earthen bunds

Boulton delay index: An empirical constant having the dimensions of time to determine the time at which the delayed yield ceases to affect the drawdown

Brackish water: Water that has more salinity than fresh water, but not as much as seawater, resulting from a mixing of seawater with fresh water

Brine water: Water saturated with large amount of salt, especially sodium chloride, due to evaporation or freezing

Bulk density: A dry weight of soil per unit volume of soil

Bulk modulus of compression of aquifer skeleton: A measure of rock’s susceptibility to volume changes in response to external force acting on it

Capillary fringe: The zone above the water table, where the water is drawn upward by capillary attraction

Capillary rise: A rise of water due to attraction of water molecules to a solid surface

Carbonate hardness: A measure of alkalinity of water caused by the presence of carbonate and bicarbonate ions

Catchment area: An area of land, where the surface water converges to a single point at a lower elevation

Catchment basin: See catchment area

Catchment factor: A significant factor that determines an amount or likelihood of flooding

Catchment water yield: A precipitation occurring as surface water flow after evapotranspiration losses and losses to soil or groundwater

Cation: A positively charged ion, which attracts a cathode in electrolysis

Cavity well: A tube well, which, being without strainers, draws its suppliers from one aquifer or water-bearing stratum only that does not go very deep and requires a very hard clayey stratum to form a strong and dependable roof over the cavity

Chemical activity: A measure of an effective concentration of species in a mixture, depending on activity of a real solution

Change of groundwater storage: A product of the area, water level fluctuation and specific yield or area, annual rainfall and rate of infiltration

Chloro-alkaline indices: Indices used for confirmation of cation-anion exchange reactions with the host rocks

Chow’s method: A method for estimation of transmissivity and storativity through pumping data

Circulatory ratio: The ratio of perimeter to basin area

Climate type: A statistics (usually, mean or variability) of weather, usually over a 30-year interval

Colour of water: The property of an object to reflect or emit light

Compressibility of the aquifer skeleton: A measure of relative volume change of a fluid or solid as a response to a pressure (or mean stress) change

Cone of depression: A reduction in the pressure head (water level) surrounding the pumped well

Confined aquifer: An aquifer sandwiched between the two impermeable layers

Constant of channel maintenance: An inverse of drainage density

Contamination: An unwanted pollution of something by another substance, which causes contamination of surrounding area

Contour elevation: A line on a map joining points of equal elevation above a given level

Contour intersection: A point or line common to lines or surfaces that intersect with contours

Contour map: A map marked with contour lines

Conversion factors: Used for taking equivalent concentration of ions

Corrosion: A chemical action on metals, which results in metals being eaten away

Cumulative: A successive addition to increasing quantity

Current electrodes: Metal rods used to transmit a current into the ground

Darcy’s law: The rate of flow through porous medium is directly proportional to the head loss and inversely proportional to the length of the flow path

Darcy's velocity: The flow per unit cross-sectional area of a porous medium

Deep drainage: A hydrological process, where water moves downward from surface water to groundwater

Deep percolation: See deep drainage

Dendritic drainage: A drainage pattern resembling a tree or the veins of a leaf

Dendritic drainage pattern: A tree-like drainage pattern formed in hard rock terrain

Denuded basin: A long-term sum of process that causes the wearing away of the Earth's surface by moving water, ice, wind and waves, leading to a reduction in elevation and relief of landforms and landscapes

Depression head: Water level difference in a well during well pumping

Depth of application: The product of the soil moisture content, apparent specific gravity of the soil and depth of penetration

Depth of effective root zone: An amount of water, occurring at depth of soil, that is available for the crop to use

Depth of irrigation: The ratio of soil moisture holding capacity to the water allowing at the peak time of plant flowering stage

Depth of penetration: The product of field capacity, moisture content and apparent specific gravity of soil, and depth of effective root zone

Debye–Huckel equation: Used to express the values of effective diameter of ions

Diameter of screen: The entrance velocity of screen to prevent incrustation and corrosion as well as to minimise friction losses

Digital elevation model (DEM): A 3D digital model representing a terrain elevation data

Direction of groundwater flow: The flow of groundwater from higher to lower elevation, generally, following the topography

Discharge: The volume of water flow (yield)

Discharge area: An area of land, where the zone of saturation is in direct contact with the ground surface

Discharge water: The water flow, which is transported through a cross-sectional area

Downstream: Movement of water in a direction in which a stream flows

Drainage area: See catchment area

Drainage basin: See catchment area

Drainage density: The total length of all streams in a drainage basin divided by the total area of drainage basin

Drainage divide: See basin divide

Drainage factor: A factor that occurs in unconfined aquifers with delayed yield

Drainage pattern: A pattern formed by the streams, rivers, and lakes in a particular drainage basin

Drainage texture: The ratio of perimeter to the number of streams

Drawdown: A change in hydraulic head in a well due to pumping

Drawdown curve: A curve that is developed between the pumping and observation wells due to pumping

Drinking water: Potable water

Dye tracing: An evolution of the ages-known float tracing method, which basically consists of throwing a buoyant object into a water flow to see, where it goes or where it emerges

Dynamic viscosity: A quantity measuring the force needed to overcome internal friction in a fluid

Dynamic water level: See drawdown

Earth's temperature: It increases 1°C for each 20 to 30 m of the Earth's depth

Effective grain size: An index of fineness of a material (10% finer and 90% coarser), indicating a very good porosity of the soil

Effective porosity: A portion of total void space of a porous material that is capable of transmitting a fluid

Effective well radius: A radial distance from the center of the pumped well at which the theoretical drawdown in the aquifer (aquifer loss) is equal to the total linear head loss in the well (i.e., total drawdown in the well neglecting turbulent loss)

Efflux velocity: An average flow rate of material emitted into the atmosphere from a source

Electrical conductivity: A degree of a specified material that conducts electricity

Elapsed time: An amount of time that passes from the beginning of an event to its end

Electrical resistivity: An intrinsic property that quantifies how strongly a given material opposes the flow of electric current

Elongation ratio: The product of length and area of the basin, which expresses the shape of the basin

Electrode array: A configuration of electrodes used for measuring either an electric current or a voltage

Equilibrate state: A state of saturation of solution

Equilibrium stage: A balancing process associated with set of inter-related stream physical adjustments that naturally maintain stream channels in their most efficient and least erosive form

Equipotential line: Line (or surface) along which the potential is constant

Equivalent weight: The formula weight of a dissolved ionic species divided by the electrical charge

Estimated water supply: A product of an area, annual rainfall and rate of infiltration of soil

European odour unit: Used to express the degree of the odour of water

Evapotranspiration: The sum of evaporation and plant transpiration from the Earth’s land and ocean surface to the atmosphere

Excess alkalinity: The measure of sodium bicarbonate in water

Excess rain: The amount of precipitation in excess of the total infiltration loss

Expansibility of water: Release of water from an aquifer by pressure

Field capacity: The amount of water the soil can hold against gravity, i.e., the maximum water that can be watered to a pot plant and it does not leak water

First quartile: Corresponding to 75% of the material being finer and 25%

coarser

Flood hazard: An area that is inundated by the flood

Flow line: A normal path that a particle of water follows under laminar flow conditions

Flow net: A graphical representation of flow lines and equipotential lines for two-dimensional, steady-state groundwater flow

Fluvial process: The process associated with rivers and streams, and the deposits and landforms created by them

Force of gravity: A force between any two objects in the universe

Form factor: The ratio of basin length to basin area

Formation loss: See aquifer loss

Fresh water: Naturally occurring water

Fresh water-salt water interface: An interface formed between the fresh water and salt water

Friction factor: A prediction of frictional energy loss in a pipe based on the velocity of fluid and resistance due to friction

Friction loss: The loss of pressure or head that occurs in pipe or duct flow due to the effect of fluid’s viscosity near surface of pipe or duct

Fully penetrating well: A well penetrating into an entire thickness of an aquifer

Genetic classification: A classification of water quality with respect to bicarbonate, sulphate and chloride types

Geochemical signatures: Ratios used for the assessment of origin of water quality

Geoelectrical parameters: Prediction of aquifer properties (hydraulic properties)

Geoelectrical survey: Detection of resistivity properties of the sub-surface layers

Geogenic origin: An origin relating to the history of the Earth from the geological processes

Geomorphology: A study of physical features of the Earth’s surface and their relation to geological structures

Ghyben–Herzberg relation: An expression of hydrostatic equilibrium existing between the densities of fresh water and seawater

Gibbs's diagram: A diagram used for the assessment of mechanisms controlling water quality

Gradation test: A procedure to assess the particle size distribution of a granular material

Grading curve: A statistical method to assigning the distribution of grades

Grain size: A diameter of individual grains of sediments

Grain size analysis: Analysis of determination of percentage of different grain sizes contained within a soil

Grain size scale: A scale of diameter of individual grains of sediment

Grid: A framework of spaced bars that are parallel to or cross each other

Groundwater: See deep drainage

Groundwater exploration: Identification of zones of permeability that feed the water flow

Groundwater flow: Movement of water in the zone of saturation

Groundwater recharge: A hydrologic process, where the water moves downward from surface water to groundwater

Groundwater quality: A measure of the condition of water relative to its important in the planning and any developmental activities

Groundwater storage: Storage of water below the sub-surface

Hazen unit: A unit to express the degree of the water colour

Humid climate: A place that has warm and damp climate

Humidity index: An index of amount of water vapour in the air

Hydraulic conductivity: The rate of flow under a unit hydraulic gradient through a unit cross-sectional area of aquifer

Hydraulic diffusivity: A property of an aquifer or confining bed defined as the ratio of the transmissivity to the storativity

Hydraulic gradient: A slope of the water table or potentiometric surface, which is caused by a change in hydraulic head over the change in distance between the two monitoring wells

Hydraulic head: See total head

Hydraulic properties: Permeability characteristics of the material

Hydraulic resistance: A useful index in semi-confined aquifers (if it is infinite, the aquifer is confined)

Hydrogeochemical facies: A diagnostic chemical aspect of groundwater solutions occurring in hydrological systems, which explain the distribution and genesis of principal groundwater types along with the water flow paths

Hydrological cycle: The sequence of conditions through which water passes from vapour in the atmosphere through precipitation upon land or water surfaces and ultimately back into the atmosphere as a result of evaporation and transpiration

Hydrological processes: A scientific study of the movement, distribution, and quality of water on Earth and other planets, including the hydrologic cycle, water resources and environmental watershed sustainability

Hydrological properties: The properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water such as porosity, effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities

Hydrological tracers: Used to assess the direction of flow, velocity and residence time (age) of water

Hydrostatic equilibrium: A hydrostatic balance, when it is at rest, or when the flow velocity at each point is constant over time. This occurs when the external forces such as gravity are balanced by a pressure gradient force

Hypsometric analysis: Measurement of heights of a river basin

Hypsometric curve: An empirical cumulative distribution function of elevations in a catchment

Hypsometric integral: An indication of cycle of erosion

Impermeable rock: A rock that does not allow water or liquid to pass through it

Incrustation: A deposition of calcium carbonate on metal surfaces

Infiltration: A process by which water on ground surface enters the soil

Infiltration number: The product of drainage density and stream frequency

Infiltration rate: The rate of soil, which is able to absorb rainfall or irrigation

Injection well: Well used for injecting fluids into the sub-surface

Intermediate zone: A part of the unsaturated zone below the root zone and above the capillary zone

Ion activity product: A measure of ions present in a solvent

Ionic-balance-error: A calculation to check analytical results

Ion exchange process: Ion exchangers are either cation exchangers that exchange positively charged ions (cations) or anion exchangers that exchange negatively charged ions (anions)

Ionic strength: A quantity representing the strength of electric field in a solution

Inverse slope method: A method used to compute the resistivity and corresponding thickness of the sub-surface layers

Irrigation efficiency: The ratio of the amount of water consumed by the crop to the amount of water supplied through irrigation (surface, sprinkler or drip irrigation)

Irrigation interval (frequency): The ratio of depth of irrigation to water usage at the peak time of plant flowering stage

Isohyetal: An imaginary line connecting places, which have an equal annual rainfall

Jackson turbidity unit: Used to express the degree of turbidity in water

Jacob's method: A method for estimation of transmissivity and storativity through pumping data

Kelley's ratio: The ratio of sodium to calcium and magnesium used for assessment of irrigation water quality

Kinematic viscosity: The ratio of dynamic viscosity to mass density, which is obtained by dividing dynamic viscosity by the fluid density

Laminar flow: A type of flow in which the fluid particles follow paths those are smooth, straight and parallel to the channel wells

Land subsidence: A gradual settling or sudden sinking of the Earth's surface owing to sub-surface movement of Earth's materials

Langelier index: An indicator of degree of saturation of calcium carbonate in water

Langelier–Ludwig's diagram: A graphical interpretation of water quality

Large diameter well: A well, which has large diameter that is under unconfined condition

Leaching requirement: An amount of water applied to flush out of root zone excess salts present in soil

Leaky confined aquifer: A low permeably layer that transmits water at sufficient quantity to well

Leakage factor: An index of leakage, representing the vertical percolation through a semi-permeable layer from above or below it (A large leakage means that the leakage is small)

Length of overland flow: The tendency of water to flow horizontally across the land surfaces

Length of screen: Division of expected discharge by velocity and open area per unit length of screen

Linear aspect: One-dimensional landforms

Linear well loss: See effective well radius

Litho-log: Data on lithological information of the sub-surface material

Magnesium ratio: The ratio of magnesium to calcium and magnesium used for assessment of irrigation water quality

Man-made pollution: See anthropogenic origin

Master curves: Theoretical curves

Mature Stage: A river slope becomes gentler and much wider as it is joined by many tributaries. It also carries a load now that has been eroded from further upstream

Mean slope: A ratio of number of contour intersections by horizontal and vertical lines to total length of both vertical and horizontal grid segments

Mechanical analysis: A technique used to characterise the materials

Median: A value at the midpoint of a frequency distribution

Milliequivalents per litre: A measure of the concentration of a solute in solution, which is obtained by dividing the concentration in milligrams per litre by equivalent (meq/l) weight of the ion, which is an expression of water quality

Milligrams per litre: A measure of the amount of dissolved solids in a solute in terms of milligrams of solute per litre (mg/l) of solution, which is an expression of water quality

Moisture index: An ability of soil to supply moisture to the plants

Molal concentration: The number of moles of solute dissolved per kilogram of solvent

Molarity: The number of moles of solute (the material dissolved) per litre of solution

Morality: A measure of concentration of a solute in a solution in terms of amount of substance in a specified amount of mass of solvent

Morphometry: The process of measuring of external shape and dimensions of landforms

Motor efficiency: The ratio of usable shaft power to electric input power

Moving average: A set of numbers, each of which is the average of the corresponding subset of a larger set of datum points

Natural gravel pack: Selective removal of fines from aquifer material surrounding the slotted or screened sections creating a natural strainer and enhancing permeability around the well

Non-carbonate hardness: A measure of calcium and magnesium salts other than carbonate and bicarbonate salts (such as calcium and magnesium of chloride and sulphate)

Non-leaky confined aquifer: No water leaking from aquifer

Non-linear well loss: See friction loss

Non-pumping water level: An initial water level before the pumping of the well

Non-uniform material: See poorly graded material

Number of watering days: A ratio of water consumption for crop to depth of irrigation

Observation well: A special well drilled in a selected location for the purpose of observing parameters such as fluid levels and pressure changes

Odour: A distinctive smell, especially an unpleasant one

Old stage (river): A river with a low gradient and low erosive energy

Open area of screen: An area that is to enter the water into the well

Overdraft: Discharge (output) exceeds recharge (input)

Oversaturation: A more dissolved solute than normal, under particular temperature and pressure

Parallel drainage pattern: A drainage pattern characterised by regularly spaced streams flowing parallel to one another over a large area

Particle size: See grain size

Peak consumptive use: The highest consumptive use during few days of crop growing season

Percent sodium: The ratio of sodium to the total cations used for the assessment of water quality for irrigation

Perimeter: A length of the boundary of the basin

Permeability: See hydraulic conductivity

Permeability index: The ratio of sodium and square root of the bicarbonate to calcium, magnesium and sodium that is used for the assessment of water quality for irrigation

pH: Potential of hydrogen, a measure of acidity or alkalinity of a solution equal to logarithm of reciprocal of concentration of hydrogen ions in moles per cubic decimetre of solution

pH_s: A saturated pH

Phreatic water: Groundwater below the water table

Piezometer: An instrument for measuring the water pressure

Piper's diagram: A graphical interpretation of water quality types

Pollution: The presence or introduction of a substance into the environment, which has harmful or poisonous effects

Polygon: A closed plane figure bounded by three or more line segments

Poorly-graded: A soil that does not have a good representation of all sizes of particles

Poorly-sorted: A soil that indicates the sediment sizes are mixed (large variance)

Porosity: A measure of the void spaces in a material, and a fraction of the volume of voids over the total volume

Porous material: A material containing pores (voids)

Potential electrodes: Porous plots with copper sulphate solution that are used to measure a potential developed by circulation of current into the ground

Potential evapotranspiration: A measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration

Precipitation: Rain, snow, sleet, or hail that falls to or condenses on the ground

Precipitation state: A solution, which is in the oversaturation state

Probable drawdown: A ratio of aquifer thickness to transmissivity

Pump efficiency: The ratio of power imparted on fluid by pump in relation to power supplied to drive the pump

Pumping period: The time required for pumping

Pumping rate: Well discharge (well yield)

Pumping test: See aquifer test

Pumping water level: See dynamic water level

Quartile: Each of four equal groups of a particular variable

Radial drainage pattern: A drainage pattern characterised by radiating streams diverging from a high central area

Radius of influence: The maximum distance at which drawdown can be detected with the usual measuring devices in the field

Rain gauge: A type of instrument used to measure the amount of rainfall (precipitation) over a set period of time

Range of size: An index of effective distribution of grain size of a material

Rational method: The product of runoff coefficient, area of catchment and precipitation

Recharge area: An intake area, where the water moves downward from surface to groundwater

Recharge volume: A product of an area and specific yield

Recovery data: The difference in groundwater head due to pumping

Rectangular drainage pattern: A drainage pattern of streams that make many right-angle bends

Reduced water level: The difference between the contour elevation and water level

Relative area: A ratio of an area between the contours to the highest area between the contours

Relative height: Elevation difference between the heighest and lowest

Relief: The difference between the maximum and minimum elevations in a basin (above mean sea level)

Relief aspect: Three-dimensional landforms

Relief ratio: The ratio of length to the difference between the maximum and minimum elevations in a basin

Relative relief: The ratio of perimeter to the difference between the maximum and minimum elevations in a basin

Replenishable groundwater: The product of the area, annual rainfall and rate of infiltration of soil

Residual drawdown: The rise in water level in a well in response to cessation of pumping

Residual sodium carbonate: The differential value between the carbonates (bicarbonate and carbonate) and alkaline earths (calcium and magnesium)

Resistance: An opposition that a substance offers to the flow of electric current

Reynold's number: A number used for the determination of fluid flow whether it is laminar or turbulent

River basin: See catchment area

Ruggedness number: The product of maximum basin relief and drainage density within drainage basin, which is a simple flow accumulation-related index

Runoff: A part of water that flows over land as surface water

Runoff coefficient: A dimensionless coefficient, which relates the amount of runoff to the amount of precipitation received

Runoff percentage: An expression of runoff in percentage, depending on the annual rainfall

Saline water: Water that contains a significant concentration of dissolved salts (mainly NaCl) and is commonly known as salt water

Salinity hazard: An excess of salt content that affects crop yields

Saturation: An index showing whether the water will tend to dissolve or precipitate a particular mineral

Saturation index: An indicator of precipitation or dissolution or equilibrium of a particular mineral in water

Saturation percentage: The percentage of moisture content of a sample of soil

Saturation pH: A calculated pH

Saturation state: See equilibrate state

Saturation zone: Those parts of the Earth's crust in which all voids are filled with water under pressure greater than atmospheric pressure

Schlumberger array: An electrode array, in which all four electrodes are placed in a line, but the distance between the current electrodes is maintained equal to or more than five times the distance between the potential electrodes

Screen entrance velocity: A low water flow through screen to ensure a long service life of well as well as to move an aquifer material, resulting in subsequent clogging of screen openings

Screen grain size: Corresponding to 60% of material being finer and 40% coarser, indicating a poor porosity of soil

Screen length: One-third of the aquifer thickness in case of confined aquifer and three-fourths of the aquifer thickness in case of unconfined condition, which is the desirable length of the screen for homogenous aquifer material

Screen parameter: A ratio of slot, velocity, screen length and screen area to screen diameter

Seawater intrusion: Entering of seawater into aquifer system due to lowering of groundwater table below the mean sea level by overpumping of groundwater

Seepage: The fluid discharged at a seep (without specific outlet)

Seepage velocity: The rate of discharge of seepage water through a porous medium per unit area of void space perpendicular to the direction of flow

Segment: A division of each part

Semi-arid climate: The climate of a region that receives the precipitation below potential evapotranspiration, but not extremely

Semi-permeable layer: See leaky confined aquifer

Shape factor: A dimensionless constant, depending on various properties of medium affecting flow other than the grain diameter on which the dimensions of the pores depend

Sieve analysis: See gradation test

Soil moisture: Water present in an unsaturated zone

Soil moisture deficit: An amount of rain needed to bring the soil moisture content back to field capacity

Soil moisture utilization: A quantity of water in excess of actual evapotranspiration and precipitation

Soil moisture zone: Sub-surface liquid water in the unsaturated zone, which is expressed as a fraction of the total porous medium volume occupied by water

Slichter's method: A method used for the estimation of specific capacity

Slope: A surface having one end at a higher level than another

Slot size of screen: A selection of slot size to prevent movement of fine aquifer material near slots so that all fines around well screen can be washed out to improve aquifer hydraulic conductivity, depending on the size and gradation of aquifer material, well discharge and water quality

Slug test: A particular type of aquifer test, where the water is quickly added or removed from a groundwater well, and the change in hydraulic head is monitored through time, to determine the near-well aquifer characteristics

Sodium adsorption ratio (SAR): The ratio of sodium to square root of the calcium and magnesium, which is a measure of soil sodicity, used for the assessment of water quality for irrigation

Sodium hazard: Water having high sodium contents, reduces the soil permeability

Solubility product: The product of its dissolved ion concentrations to the power of their stoichiometric coefficients

Sorting coefficient: A variation in the grain sizes that make up sediment

Specific capacity: The ratio of discharge (yield) to drawdown

Specific capacity index: An expression of the specific capacity of the well for unit thickness of the aquifer tapped

Specific drawdown: A ratio of resulting drawdown to well discharge

Specific electrical conductance: An ability of water to transmit an electrical current, depending on the concentration and charge of ions present in water

Specific electrical resistance: See electrical resistivity

Specific gravity: The ratio of the density of a substance to the density of a reference substance; equivalently, it is the ratio of the mass of a substance to the mass of a reference substance for the same given volume

Specific retention: The ratio of the volume of water it will retain after saturation against the force of gravity to its own volume

Specific weight: The weight per unit volume of a material

Specific yield: The volume of water released from groundwater storage per unit surface area of aquifer per unit decline in water table

Static water level: An elevation or water level in a well when the pump is not operating

Steady-state: A stable condition that does not change over time

Step drawdown: A single-well pumping test to investigate the performance of a pumping well under controlled variable discharge conditions

Storage coefficient: The volume of water released from storage per unit decline in hydraulic head in an aquifer per unit area of the aquifer due to compressibility of aquifer skeleton and expansibility of water

Storativity: See storage coefficient

Stream frequency: The ratio of a number of streams in a drainage basin to the area of a basin

Stream length: The length of stream of a particular order of drainage basin

Stream line: A path traced out by a mass less particles as it moves with the flow

Stream number: Occurrence of a number of streams of the same stream order in a specified drainage basin

Stream order: The flow of water in a specific way

Strong acid: Acid related to chloride, sulphate and nitrate ions

Surface water storage: Water that is accumulated on the soil surface or under ground

Taste of water: Human perceptions of water quality

Temperature: A degree or intensity of heat present in a substance

Theis’s method: A method for estimation of transmissivity and storativity through pumping data

Theis’s recovery method: A recovery pumping test for estimation of transmissivity

Thiessen Polygon method: Used to compute the average precipitation, following the polygon procedure (see polygon)

Third quartile: Corresponding to 25% of the material being finer and 75% coarser

Tidal efficiency: A degree of correlation between the fluctuations of piezometric level and tidal levels

Tide water: A water brought or affected by tides

Time of irrigation: The ratio of average depth of the water flowing over the land, and the rate of infiltration of soil to the area covered with water

Topographic lows: A low topography (gentle slope or plain area)

Topographic highs: A high topography (steep slope)

Total alkalinity: A measure of alkalinity of substances present in water expressed as equivalent of calcium carbonate

Total area irrigated: The ratio of well discharge to the depth of irrigation

Total dissolved solids: A measure of a combined content of all inorganic and organic substances contained in a water

Total hardness: The concentration of calcium and magnesium ions expressed as equivalent of calcium carbonate

Total head: A sum of depth required and friction loss or a sum of the elevation head, the pressure head and the velocity head at a given point in an aquifer

Total rain: The product of precipitation (rainfall) with time

Tracer: A matter or energy carried by water, which gives information concerning the direction and/or of velocity of water and also residence time of water (age)

Trellis drainage pattern: A trellis-like appearance of drainage system formed from steep slopes on the sides of mountains

Transmissivity: The rate at which the groundwater flows through an entire thickness of the aquifer

Tributary: Smaller rivers/streams that join the main river

Trilinear diagram: See Piper’s diagram

Turbidity: The cloudiness or haziness of a fluid due to suspended and colloidal organic and inorganic material

Turbulent flow: A flow regime characterized by chaotic changes in pressure and flow velocity

Unconfined aquifer: An aquifer which has a water table

Under-saturation: A zone that has less amount of solute than what is required to saturate under particular temperature

Undisturbed core: A cylindrical sample extracted from the ground

Uniformity coefficient: An index of grading or particle size distribution of a soil material

Unsaturated state: A solution in a dissolute state

Unsaturated zone: A zone between the land surface and the water table

Unsteady state: A unstable condition that changes over time

Upconing: A process by which the saline water underlying fresh water in an aquifer rises upward into freshwater zone due to pumping in an island area

Upstream: Moving of water in a opposite direction from that in which a stream flows

USSL's diagram: A diagram used for the assessment of water quality for irrigation

Vadose water: Groundwater suspended or in circulation above the water table

Vadose zone: See unsaturated zone

Velocity of groundwater flow: See Darcy's velocity

Vertical electrical sounding (VES): A geophysical method for investigation of a geological medium, which is based on the estimation of the electrical resistivity of the medium

Void ratio: The ratio of volume of void space to the total volume of solid substance

Volume resistivity: See electrical resistivity

Volumetric water content: The volume of water per unit volume of soil expressed as percentage

Water balance: An evaluation of all water supply sources and corresponding discharges with respect to an aquifer or a drainage basin

Water basin: See catchment area

Water budget: See water balance

Water content: The ratio of the mass of water in a sample to the mass of solids in the sample expressed as a percentage

Water deficit: The amount of water by which the potential evapotranspiration exceeds actual evapotranspiration

Water divide: See basin divide

Water flow velocity: See Darcy’s law

Water pressure: A pressure exerted by water or hydraulic pressure or hydrostatic pressure

Water requirement: A product of population, water consumption and time or the ratio of the weight of water absorbed during the growth of a plant to the dry matter produced by the plant product

Watershed: The area of high land that separates two basins

Water surplus: An amount or quantity in excess of what is needed

Water table: A surface in an unconfined aquifer, which is open to atmosphere

Water vapour: One state of water (gaseous phase) within the hydrosphere, which can be produced from the evaporation or boiling of liquid water or from the sublimation of ice

Weak acid: Acid related to bicarbonate and carbonate ions

Well casing: A solid piece of pipe used to keep a well open in either unconsolidated materials or unstable rock

Well design: A process of specifying materials and dimensions for a well

Well efficiency: The ratio of the theoretical drawdown in the formation of the actual drawdown in the well

Well function: An infinite series term that appears in the Theis equation of groundwater flow

Well graded: A soil that has a wide range of particle sizes and a substantial amount of the intermediate particle sizes

Well interference: An interference of water levels, when the wells are spaced close together and their cones of depressions overlap

Well loss: Head loss caused by flow through a screen and inside a well, arising from turbulent flow

Well screen: A screen that serves as an intake portion of well constructed in unconsolidated or semi-consolidated aquifers

Well sorted: A soil indicates that the sediment sizes are similar (low variance)

Well yield: See well discharge

Wenner array: An electrode array in which the potential electrodes are located in a line with the current electrodes, all four being equidistant from one another and disposed symmetrically with respect to a central point

Wilcox's diagram: A diagram used for the assessment of water quality for irrigation

Yield factor: The ratio of thickness to specific capacity

Yield capacity: See yield factor

Young stage (river): The beginning of a river, where it flows quickly with a lot of energy

Zone of saturation: See unsaturated zone

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