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(UGC AUTONOMOUS)
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DEPARTMENT OF CIVIL ENGINEERING

Hydrology & Water Resources Engineering

LECTURE NOTESR18

B. TECH
III YEAR - I SEM (Sec- A&B)
Academic Year 2020-21

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UNIT I
INTRODUCTION TO ENGINEERING HYDROLOGY AND ITS APPLICATIONS

Introduction

The amount of precipitation flowing over the land surface and the evapotranspiration losses from land and water bodies were discussed in Lesson 2.1. This water ultimately is returned to the sea through various routes either overland or below ground. Evaporation from the ocean, which is actually a large water body, contributes to the bulk of water vapour to the atmosphere, driven by the energy of the sun. This process completes the ***hydrologic cycle*** (Figure 1), which keeps the water content of the Earth in a continuous dynamic state.

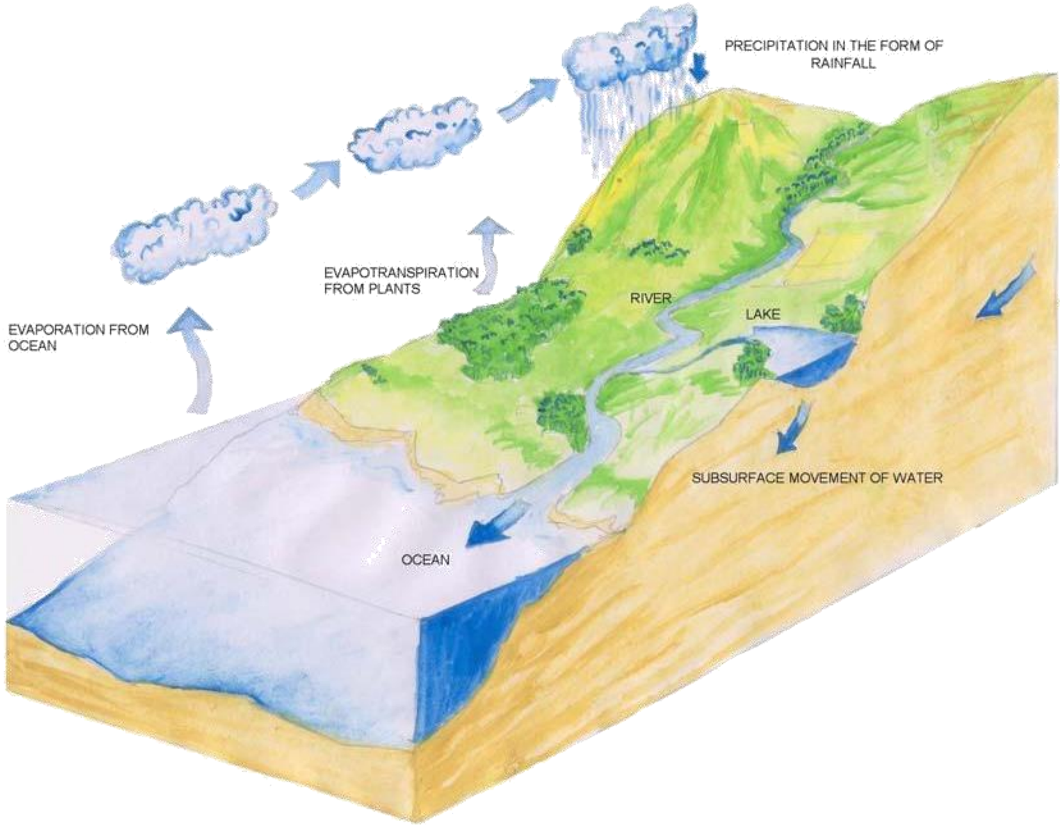


FIGURE 1. HYDROLOGIC CYCLE

The raindrops as they fall on the earth and flow down the land surface to meet streams and rivers. Part of the water, as it flows down the land surface, infiltrates into the soil and ultimately contributes to the ground water reserve.

Overland flow and inter flow

During a precipitation event, some of the rainfall is intercepted by vegetation before it reaches the ground and this phenomenon is known as ***interception***. At places without any vegetation, the rain directly touches the land surface.

This water can infiltrate into the soils, form puddles called the ***depression storage***, or flow as a thin sheet of water across the land surface. The water trapped in puddles ultimately evaporates or infiltrates.

If the soil is initially quite dry, then most of the water infiltrates into the ground. The amount of rainfall in excess of the infiltrated quantity flows over the ground surface following the land slope. This is the ***overland flow***.

The portion that infiltrates moves through an unsaturated portion of the soil in a vertical direction for some depth till it meets the water table, which is the free surface of a fully saturated region with water (the ground water reserve). Part of the water in the ***unsaturated zone*** of the soil (also called the ***vadose zone***) moves in a lateral direction, especially if the ***hydraulic conductivity*** in the horizontal direction is more than that in vertical direction and emerges at the soil surface at some location away from the point of entry into the soil. This phenomenon is known as ***interflow***. Figure 2 illustrates the flow components schematically.

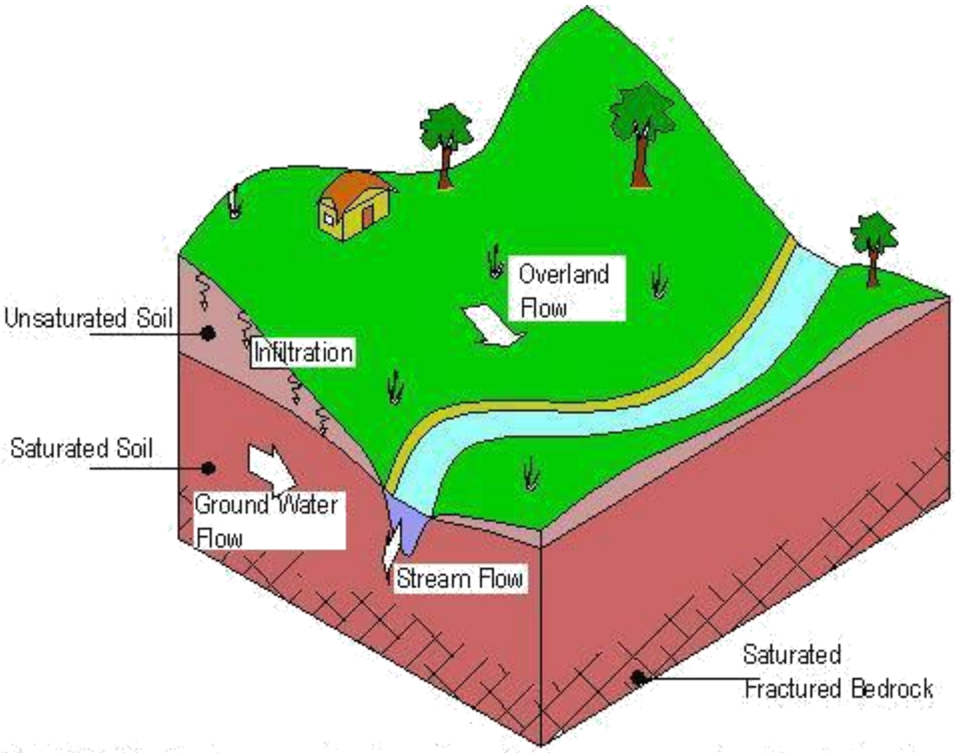


FIGURE 1. Surface and sub-surface flow components of hydrologic cycle

Hydraulic conductivity is a measure of the ability of a fluid to flow through a porous medium and is determined by the size and shape of the pore spaces in the medium and their degree of interconnection and also by the viscosity of the fluid. Hydraulic conductivity can be expressed as the volume of fluid that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow

Stream flow and groundwater flow

If the unsaturated zone of the soil is uniformly permeable, most of the infiltrated water percolates vertically. Infiltrated water that reaches the ground water reserve raises the water table. This creates a difference in potential and the inclination of the water table defines the variation of the ***piezometric head*** in horizontal direction. This difference in energy drives the ground water from the higher to the lower head and some of it ultimately reaches the stream flowing through the valley.

This contribution of the stream flow is known as Base flow, which usually is the source of dry-weather flow in perennial streams.

During a storm event, the overland flow contributes most of the immediate flow of the stream. The total flow of the stream, however, is the sum ofoverland flow, interflow and ***base flow***. It must be remembered that the rates at which these three components of runoff move varies widely. Stream flow moves fastest, followed by interflow and then ground water flow, which may take months and sometimes even years to reach the stream.

Note that for some streams, the water table lies quite some distance below the bottom of the stream. For these streams, there is a loss of water from the river bed percolating into the ground ultimately reaching the water table. The reason for a low water table could possibly be due to natural geographic conditions, or a dry climate, or due to heavy pumping of water in a nearby area.

The hydrograph and hyetograph

As the name implies, Hydrograph is the plot of the stream flow at a particular location as a function of time. Although the flow comprises of the contributions from overland flow, interflow and groundwater flow, it is useful to separate only the groundwater flow (the base flow) for hydrograph analysis, which is discussed in Lesson 2.3.

In Lesson 2.1, precipitation was discussed. The hyetograph is the graphical plot of the rainfall plotted against time. Traditionally, the hyetograph is plotted upside down as shown in Figure 3, which also shows a typical hydrograph and its components. Splitting up of a complete stream flow hydrograph into its components requires the knowledge of the geology of the area and of the factors like surface slope, etc. Nevertheless, some of the simpler methods to separate base flow are described subsequently.

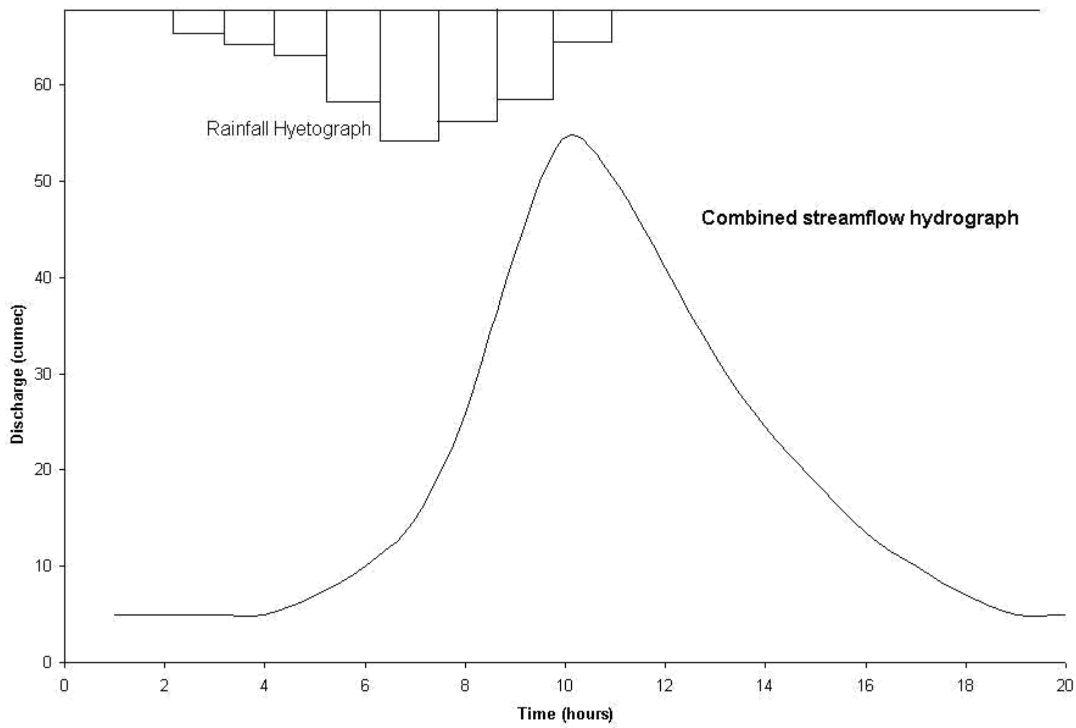


FIGURE 2. Rainfall hyetograph and corresponding flow hydrograph

The combined hydrograph can be split up into two parts: The base flow (Figure 4) and the overland flow added to interflow (Figure 5)

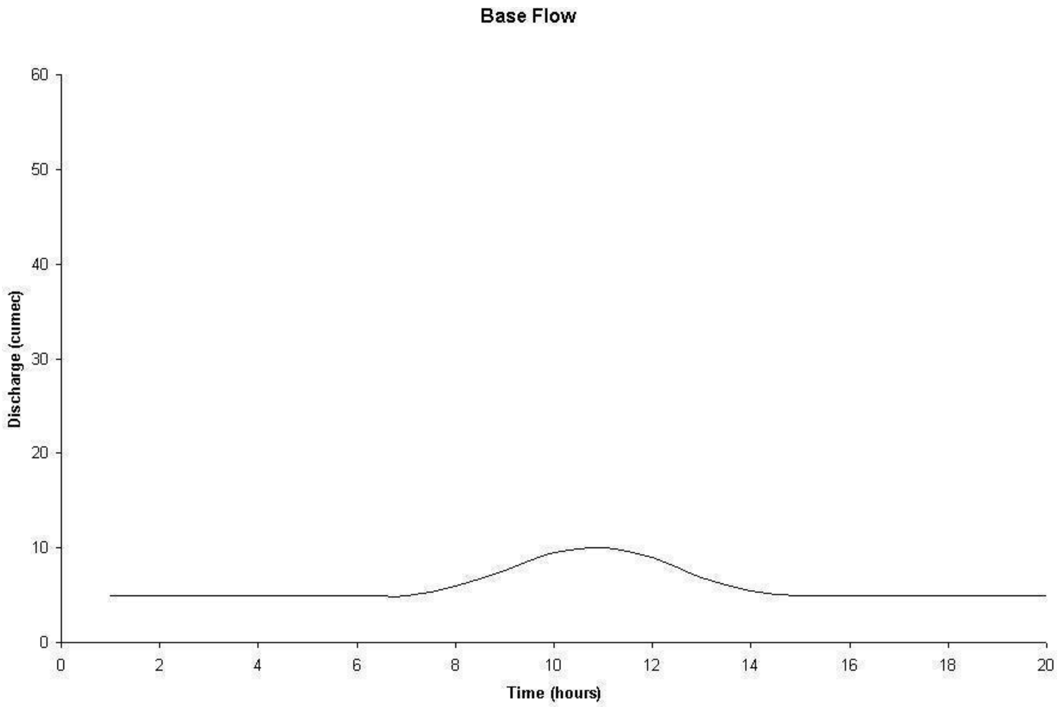


FIGURE 3. Typical baseflow discharge hydrograph

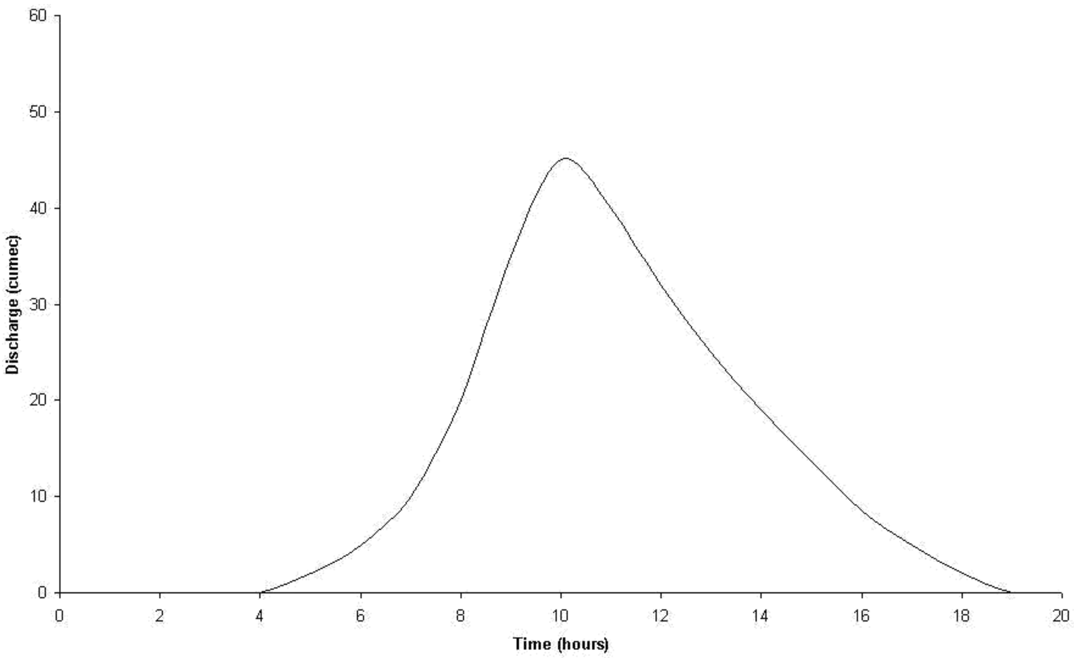


FIGURE 5. Overland flow and interlfow combined hydrogrph

Effective rainfall

A part of the rainfall reaching the earth's surface infiltrates into the ground and finally joins the ground water reservoirs or moves laterally as interflow. Of the interflow, only the quick response or prompt interflow contributes to the immediate rise of the stream flow hydrograph. Hence, the rainfall component causing perceptible change in the stream flow is only a portion of the total rainfall recorded over the catchment. This rainfall is called the effective rainfall.

The infiltration capacity varies from soil to soil and is also different for the same soil in its moist and dry states. If a soil is initially dry, the infiltration rate

(or the infiltration capacity of the soil) is high. If the precipitation is lower than the infiltration capacity of the soil, there will be no overland flow, though interflow may still occur. As the rainfall persists, the soil become moist and infiltration rate decreases, causing the balance precipitation to produce surface runoff. Mathematical representation of the infiltration capacity and the methods to deduct infiltration for finding effective rainfall is described later in this lesson.

Methods of base flow separation:

Consider the total runoff hydrograph shown in Figure 3, for which the corresponding effective rainfall hyetograph over the catchment is known. In this example, the flow in the stream starts rising at about 4 hours, and the peak is seen to reach at about 10.5 hours. The direct runoff is presumed to end at about 19.5 hours. Though we have separately shown the base flow and the direct runoff in Figures 4 and 5, it is only a guess, as what is observed flowing in the stream is the total discharge. A couple of procedures are explained in the following sub-sections to separate the two flows. For this, we consider another hydrograph (Figure 6), where the total flow is seen to be reducing initially, and then a sudden rise takes place, probably due to a sudden burst of rainfall.

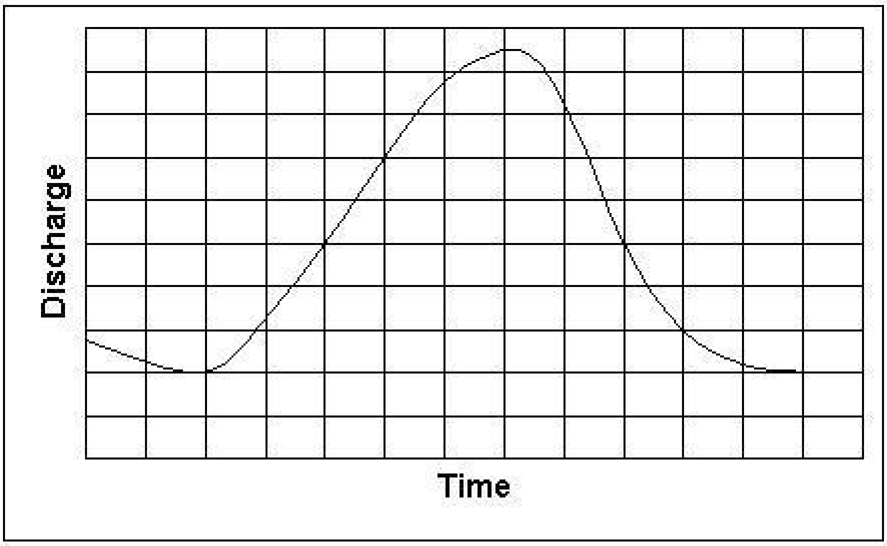


FIGURE 6. A typical hydrograph requiring base flow separation

Method 1

One method to separate the base flow from the total runoff hydrograph is to join points X and Z as shown in Figure 7. This method is considered not very accurate, though.

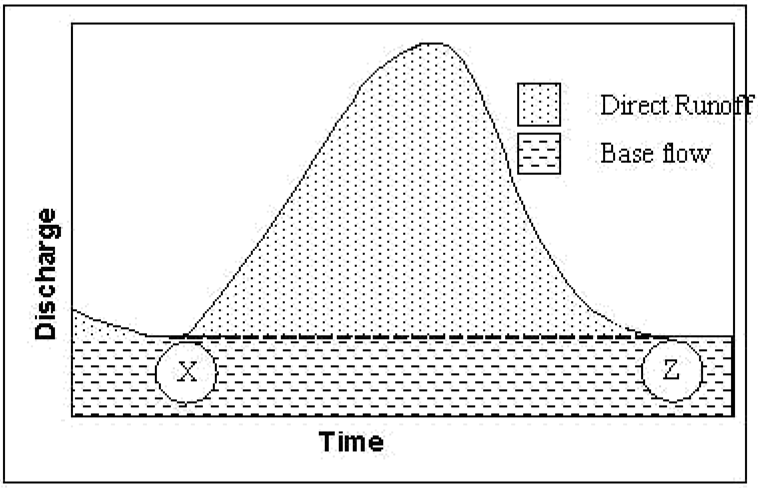


FIGURE 7. Method 1 to separate base flow

Method 2

This method suggests the extension of the base flow graph (Figure 8) along its general trend before the rise of the hydrograph up to a point P directly below the runoff hydrograph peak. From P, a straight line PQ is drawn to meet the hydrograph at point Q, which as separated from P in the time scale by an empirical relation given as:

$$N \text{ (in days)} = 0.862\, A^{0.2} \quad (1)$$

Where, A is the area of the drainage basin in square kilometers.

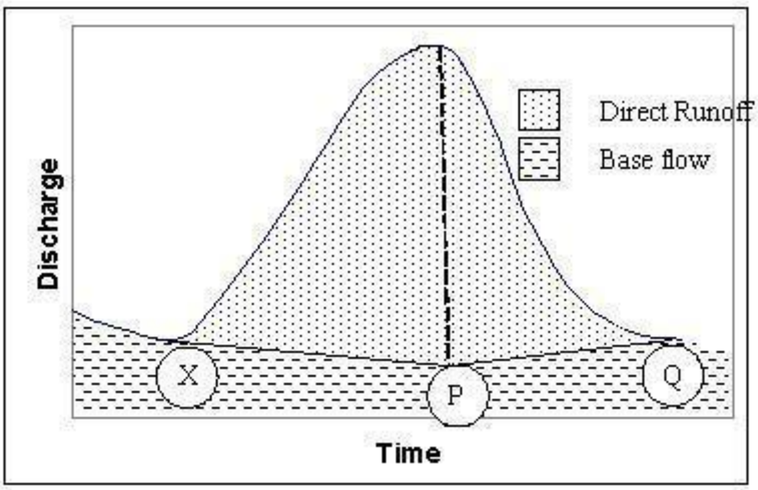


FIGURE 8. Method 2 to separate base flow

Method 3

The third method makes use of composite base flow recession curve, as shown in Figure 9. The following points are to be kept in mind:

X – A follows the trend of the initial base flow recession curve prior to the start of the direct runoff hydrograph

B – Q follows the trend of the later stage base flow recession curve.

B is chosen to lie below the point of inflection (C) of the hydrograph.

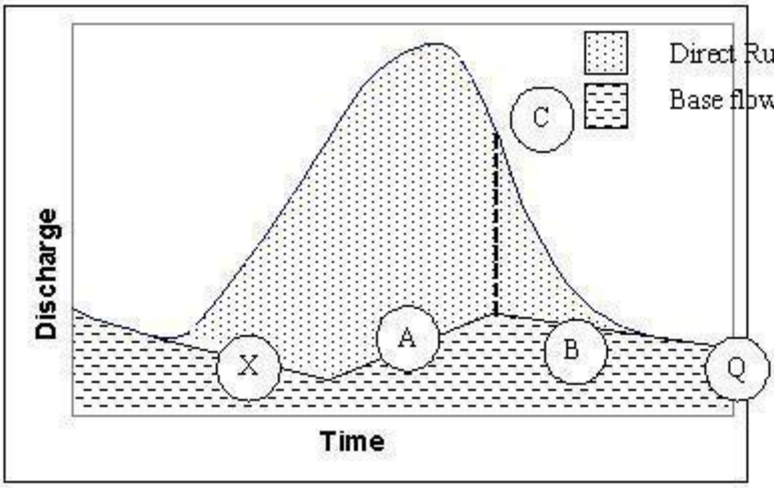


FIGURE 9. Method 3 for base flow separation

The hydrograph after separating and the base flow results in what is called the ***Direct Runoff hydrograph.***

Estimation of infiltration:

The rate at which water infiltrates into a ground is called the ***infiltration capacity.*** When a soil is dry, the infiltration rate is usually high compared to when the soil is moist. For an initially dry soil subjected to rain, the infiltration capacity curve shows an exponentially decaying trend as shown in Figure 10.

The observed trend is due to the fact that when the soil is initially dry, the rate of infiltration is high but soon decreases, as most of the soil gets moist. The rate of infiltration reaches a uniform rate after some time.

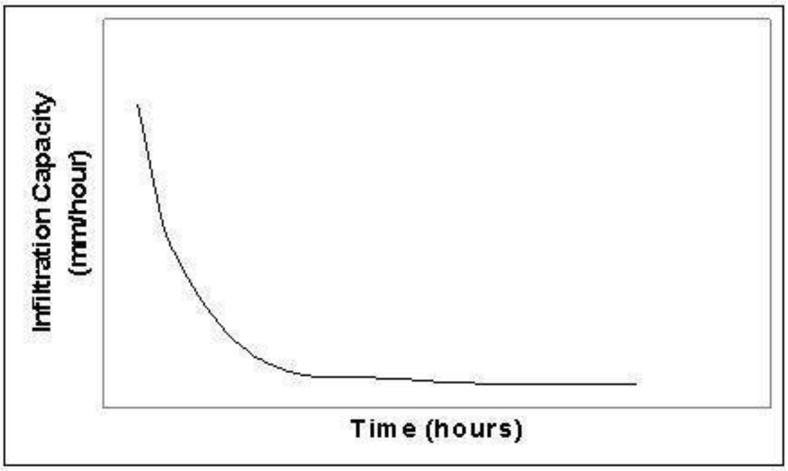


FIGURE 10. Infiltration rate decreasing as more water infiltrates

Interestingly, if the supply of continuous water from the surface is cutoff, then the infiltration capacity starts rising from the point of discontinuity as shown in below.

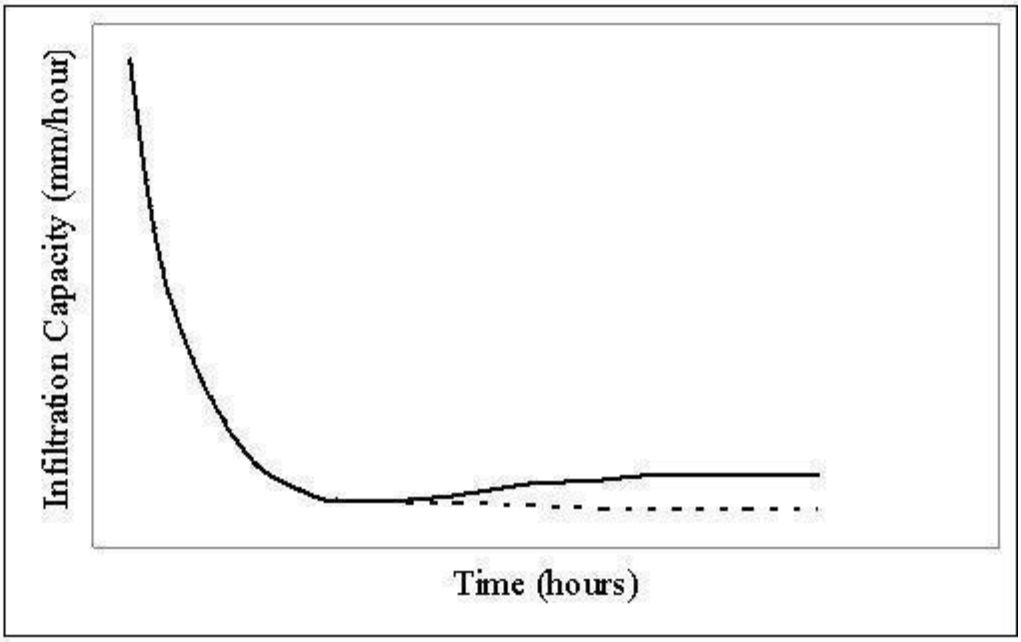


FIGURE 11. Infiltration capacity rising after supply from top is cut off

For consistency in hydrological calculations, a constant value of infiltration rate for the entire storm duration is adopted. The average infiltration rate is called the Infiltration Index and the two types of indices commonly used are explained in the next section.

Infiltration indices

The two commonly used infiltration indices are the following:

φ – index
W – index

φ - index

This is defined as the rate of infiltration above which the rainfall volume equals runoff volume, as shown in Figure 12.

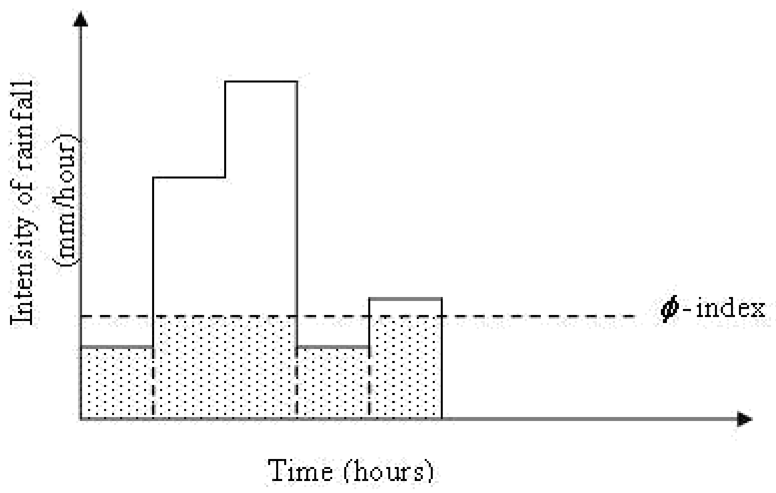


FIGURE 12. Illustrating the ϕ- index

The method to determine the - index would usually involve some trial. Since the infiltration capacity decreases with a prolonged storm, the use of an average loss rate in the form of - index is best suited for design storms occurring on wet soils in which case the loss rate reaches a final constant rate prior to or early in the storm. Although the - index is sometimes criticized as being too simple a measure for infiltration, the concept is quite meaningful in the study of storm runoff from large watersheds. The evaluation of the infiltration process is less precise for large watersheds. The data is never sufficient to derive an infiltration curve. Under the circumstances, the - index is the only feasible alternative to predict the infiltration from the storm.

The W – index

This is the average infiltration rate during the time when the rainfall intensity exceeds the infiltration rate.

Thus, ***W*** may be mathematically calculated by dividing the total infiltration (expressed as a depth of water) divided by the time during which the rainfall intensity exceeds the infiltration rate. Total infiltration may be fund out as under:

Total infiltration = Total precipitation – Surface runoff – Effective storm retention

The ***W*** – index can be derived from the observed rainfall and runoff data. It differs from the - index in that it excludes surface storage and retention. The index does not have any real physical significance when computed for a multiple complex watershed. Like the phi-index the - index, too is usually used for large watersheds.

UNIT II
DISTRIBUTION OF RUNOFF

Introduction

It was explained what a hydrograph is and that it indicates the response of water flow of a given catchment to a rainfall input. It consists of flow from different phases of runoff, like the overland flow, interflow and base flow. Methods to separate base flow from the total stream flow hydrograph to obtain the direct runoff hydrograph as well as infiltration loss from the total rainfall hyetograph to determine the effective rainfall have been discussed. In this lesson, a relationship between the direct runoff hydrograph of a catchment observed at a location (the catchment outlet) and the effective rainfall over the catchment causing the runoff are proposed to be dealt with.

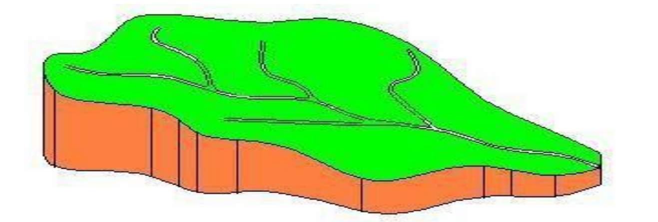
We start with discussing how the various aspects of a catchment's characteristics affects the shape of the hydrograph.

Hydrograph and the catchment's characteristics

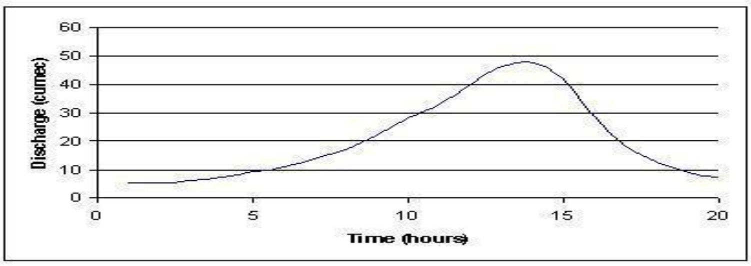
The shape of the hydrograph depends on the characteristics of the catchment. The major factors are listed below.

Shape of the catchment

A catchment that is shaped in the form of a pear, with the narrow end towards the upstream and the broader end nearer the catchment outlet (Figure 1a) shall have a hydrograph that is fast rising and has a rather concentrated high peak (Figure 1b).



(a)



(b)

FIGURE 2. (a) Catchment with narrow end towards outlet
(b) Corresponding hydrograph for a hypothetical rainfall

A catchment with the same area as in Figure 1 but shaped with its narrow end towards the outlet has a hydrograph that is slow rising and with a somewhat lower peak (Figure 2) for the same amount of rainfall.

Though the volume of water that passes through the outlets of both the catchments is same (as areas and effective rainfall have been assumed same for both), the peak in case of the latter is ***attenuated.***

Size of the catchment

Naturally, the volume of runoff expected for a given rainfall input would be proportional to the size of the catchment. But this apart, the response characteristics of large catchment (say, a large river basin) is found to be significantly different from a small catchment (like agricultural plot) due to the relative importance of the different phases of runoff (overland flow, inter flow, base flow, etc.) for these two catchments. Further, it can be shown from the mathematical calculations of surface runoff on two impervious catchments

(like urban areas, where infiltration becomes negligible), that the non-linearity between rainfall and runoff becomes perceptible for smaller catchments.

Slope

Slope of the main stream cutting across the catchment and that of the valley sides or general land slope affects the shape of the hydrograph. Larger slopes generate more velocity than smaller slopes and hence can dispose off runoff faster. Hence, for smaller slopes, the balance between rainfall input and the runoff rate gets stored temporally over the area and is able to drain out gradually over time. Hence, for the same rainfall input to two catchments of the same area but with with different slopes, the one with a steeper slope would generate a hydrograph with steeper rising and falling limits.

Here, two catchments are presented, both with the same are, but with different slopes. A similar amount of rainfall over the flatter catchment (Figure

3) produces a slow-rising moderated hydrograph than that produced by the steeper catchment (Figure 4).

Effect of rainfall intensity and duration on hydrograph

If the rainfall intensity is constant, then the rainfall duration determines in part the peak flow and time period of the surface runoff.

The concept of ***Isochrones*** might be helpful for explaining the effective of the duration of a uniform rainfall on the shape of hydrograph. Isochrones are imaginary lines across the catchment (see Figure 5) from where water particles traveling downward take the same time to reach the catchment outlet.

If the rainfall event starts at time zero, then the hydrograph at the catchment outlet will go on rising and after a time‘ t’, the flow from the isochrone ***I*** would have reached the catchment outlet. Thus, after a gap of time t, all the area A1 contributes to the outflow hydrograph.

Continuing in this fashion, it can be concluded that after a lapse of time '4 t', all the catchment area would be contributing to the catchment outflow, provided the rain continues to fall for atleast up to a time 4 t. If rainfall continues further, then the hydrograph would not increase further and thus would reach a plateau.

Effect of spatial distribution of rainfall on hydrograph

The effect of spatial distribution of rainfall, that is, the distribution in space, may be explained with the catchment image showing the isochrones as in Figure 6. Assume that the regions between the isochrones receive different amounts of rainfall (shown by the different shades of blue in the figure).

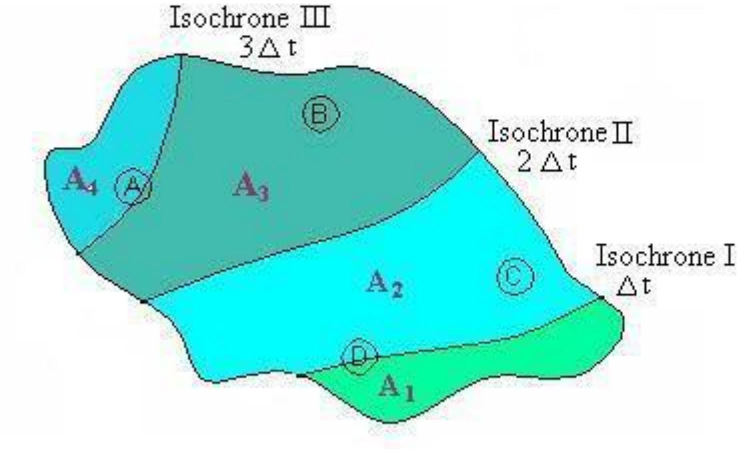


FIGURE 6. Areas of catchment subjected to different amounts of rainfall

If it is assumed now that only area A_1 receives rainfall but the other areas do not, then since this region is nearest to the catchment outlet, the resulting hydrograph immediately rises. If the rainfall continues for a time more than ' t', then the hydrograph would reach a saturation equal to $r_e.A_1$, where r_e is the intensity of the effective rainfall.

Assume now that a rainfall of constant intensity is falling only within area A_4, which is farthest from the catchment outlet. Since the lower boundary of A_4 is the Isochrone III, there would be no resulting hydrograph till time '3 t'.

If the rain continues beyond a time '4 t', then the hydrograph would reach a saturation level equal to r_e A_4 where r_e is the effective rainfall intensity.

Direction of storm movement

The direction of the storm movement with respect to the orientation of the catchments drainage network affects both the magnitude of peak flow and the duration of the hydrograph. The storm direction has the greatest effect on elongated catchments, where storms moving upstream tend to produce lower peaks and broader time base of surface runoff than storms that move downstream towards the catchment outlet. This is due to the fact that for an upstream moving storm, by the time the contribution from the upper catchment reaches the outlet, there is almost no contribution from the lower watershed.

Rainfall intensity

Increase in rainfall intensity increases the peak discharge and volume of runoff for a given infiltration rate. In the initial phases of the storm, when the soil is dry, a rainfall intensity less than infiltration rate produces no surface runoff. Gradually, as the rain progresses, the soil saturates and the infiltration rate reduces to a steady rate.

The relation between rainfall intensity and the discharge, strictly speaking, is not linear, which means that doubling the rainfall intensity does not produce a doubling of the hydrograph peak value. However, this phenomenon is more pronounced for small watersheds, such as an urban area. However in the catchment scale, due to the uncertainty of all the hydrological parameters, it might be assumed that the rainfall runoff relation follows a linear relationship. This assumption is made use of in the unit hydrograph concept, which is explained in the next section.

Unit Hydrograph

The Unit Hydrograph (abbreviated as UH) of a drainage basin is defined as a hydrograph of direct runoff resulting from one unit of effective rainfall which is uniformly distributed over the basin at a uniform rate during the specified period of time known as unit time or unit duration. The unit quantity of effective rainfall is generally taken as 1mm or 1cm and the outflow hydrograph is expressed by the discharge ordinates. The unit duration may be 1 hour, 2 hour, 3 hours or so depending upon the size of the catchment and storm characteristics. However, the unit duration cannot be more than the time of concentration, which is the time that is taken by the water from the furthest point of the catchment to reach the outlet.

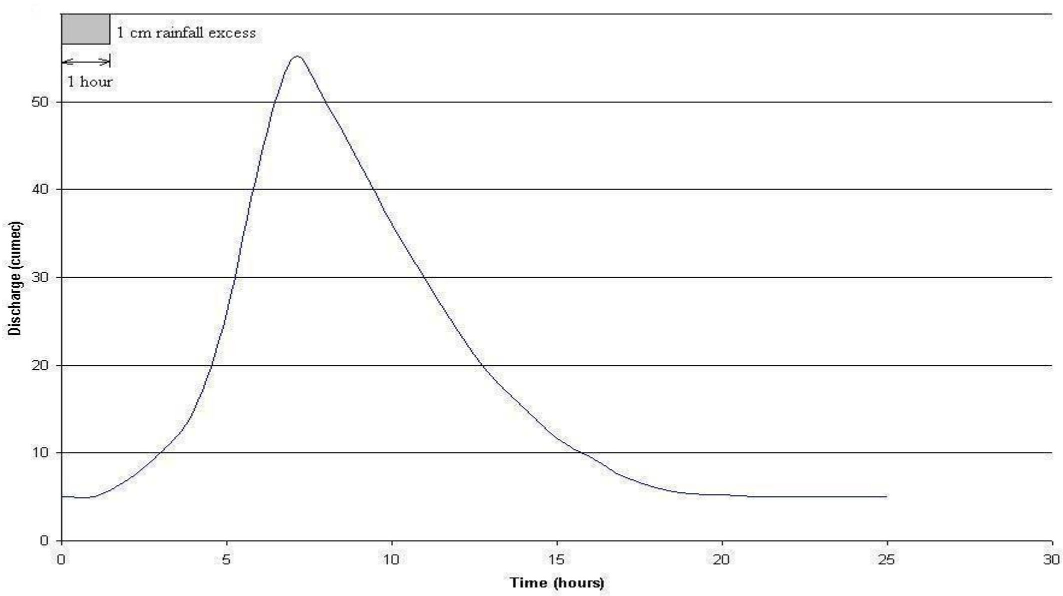


FIGURE 7. A typical unit hydrograph

Unit hydrograph

Assumptions

The following assumptions are made while using the unit hydrograph principle:

1. Effective rainfall should be uniformly distributed over the basin, that is, if there are ‘N’ rain gauges spread uniformly over the basin, then all the gauges should record almost same amount of rainfall during the specified time.
2. Effective rainfall is constant over the catchment during the unit time.
3. The direct runoff hydrograph for a given effective rainfall for a catchment is always the same irrespective of when it occurs. Hence, any previous rainfall event is not considered. This antecedent precipitation is otherwise important because of its effect on soil-infiltration rate, depressional and detention storage, and hence, on the resultant hydrograph.
4. The ordinates of the unit hydrograph are directly proportional to the effective rainfall hyetograph ordinate. Hence, if a 6-h unit hydrograph due to 1 cm rainfall is given, then a 6-h hydrograph due to 2 cm rainfall would just mean doubling the unit hydrograph ordinates. Hence, the base of the resulting hydrograph (from the start or rise up to the time when discharge becomes zero) also remains the same.

Unit hydrograph limitations

Under the natural conditions of rainfall over drainage basins, the assumptions of the unit hydrograph cannot be satisfied perfectly. However, when the hydrologic data used in the unit hydrograph analysis are carefully selected so that they meet the assumptions closely, the results obtained by the unit hydrograph theory have been found acceptable for all practical purposes.

In theory, the principle of unit hydrograph is applicable to a basin of any size. However, in practice, to meet the basic assumption in the derivation of the unit hydrograph as closely as possible, it is essential to use storms which are uniformly distributed over the basin and producing rainfall excess at uniform rate. Such storms rarely occur over large areas. The size of the catchment is, therefore, limited although detention, valley storage, and infiltration all tend to minimize the effect of rainfall variability. The limit is generally considered to be about 5000 sq. km. beyond which the reliability of the unit hydrograph method diminishes. When the basin area exceeds this limit, it has to be divided into sub-basins and the unit hydrograph is developed for each sub-basin. The flood discharge at the basin outlet is then estimated by combining the sub-basin floods, using ***flood routing*** procedures.

Note:

Flood Routing: This term is used to denote the computation principles for estimating the values of flood discharge with time and in space, that is, along the length of a river. Details about flood routing procedures may be had from the following book:

M H Chaudhry (1993) Open channel hydraulics, Prentice Hall of India

Application of the unit hydrograph

Calculations of direct runoff hydrograph in catchment due to a given rainfall event (with recorded rainfall values), is easy if a unit hydrograph is readily available. Remember that a unit hydrograph is constructed for a unit rainfall falling for a certain T-hours, where T may be any conveniently chosen time duration. The effective rainfall hyetograph, for which the runoff is to be calculated using the unit hydrograph, is obtained by deducting initial and infiltration losses from the recorded rainfall. This effective rainfall hyetograph is divided into blocks of T-hour duration. The runoff generated by the effective rainfall for each T-hour duration is then obtained and summed up to produce the runoff due to the total duration.

Direct runoff calculations using unit hydrograph

Assume that a 6-hour unit hydrograph (UH) of a catchment has been derived, whose ordinates are given in the following table and a corresponding graphical representation is shown in Figure 8.

Time (hours)	Discharge (m^3/s)
0	0
6	5
12	15
18	50
24	120
30	201
36	173
42	130
48	97
54	66
60	40
66	21
72	9
78	3.5
84	2

Assume further that the effective rainfall hyetograph (ERH) for a given storm on the region has been given as in the following table:

Time (hours)	Effective Rainfall (cm)
0	0
6	2
12	4
18	3

This means that in the first 6 hours, 2cm excess rainfall has been recorded, 4cm in the next 6 hours, and 3cm in the next.

The direct runoff hydrograph can then be calculated by the three separate hyetographs for the three excess rainfalls by multiplying the ordinates of the hydrograph by the corresponding rainfall amounts. Since the rainfalls of 2cm,

4cm and 3cm occur in successive 6-hour intervals, the derived DRH corresponding to each rainfall is delayed by 6 hours appropriately.

DRH for 2cm excess rainfall in 0-6 hours

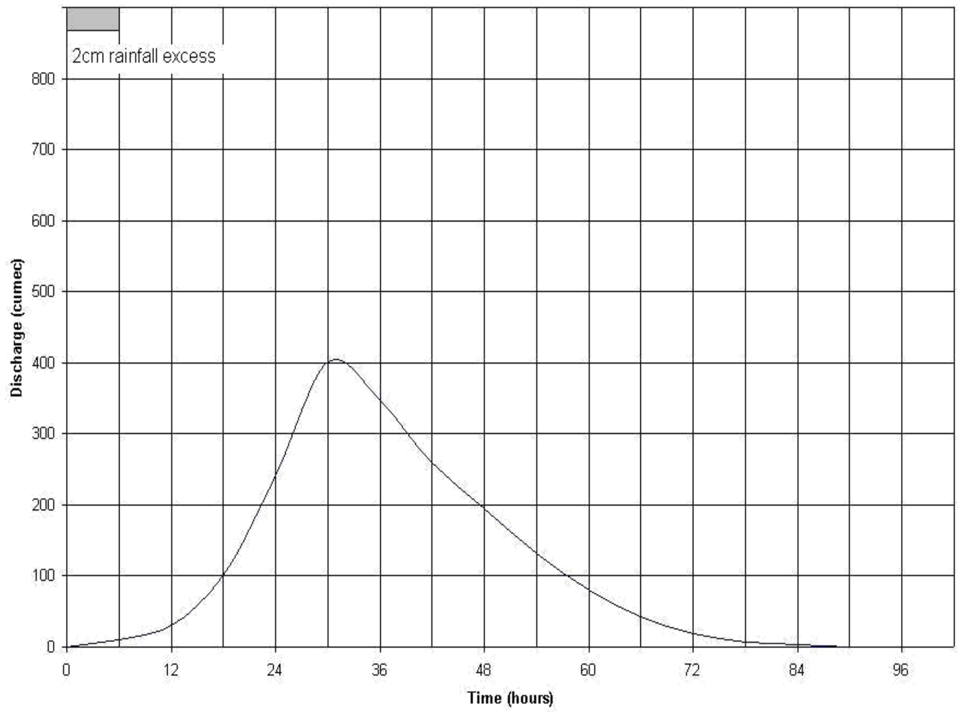


FIGURE 9. DRH corresponding to 2cm excess rainfall in 0 - 6 hours

DRH for 4cm excess rainfall in 6-12 hours

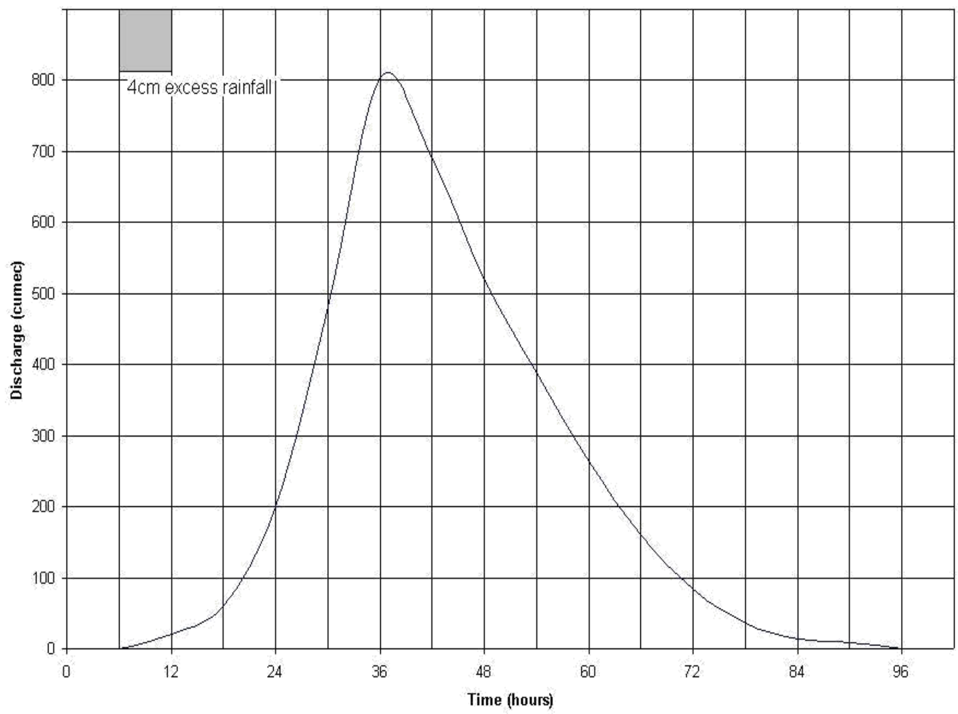


FIGURE 10. DRH corresponding to 4cm excess rainfall during 6 - 12 hours

DRH for 3cm excess rainfall in 12-18

hours

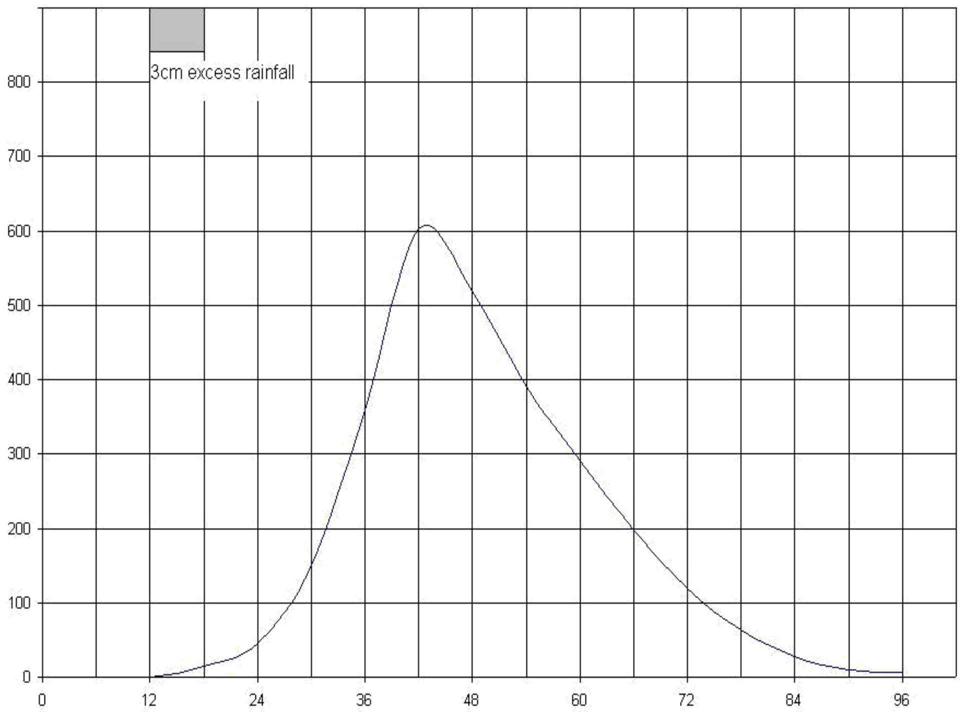


FIGURE 11. DRH corresponding to 3cm excess rainfall during 12 - 18 hours

The final hydrograph is found out by adding the three individual hydrographs, as shown in Figure 12.

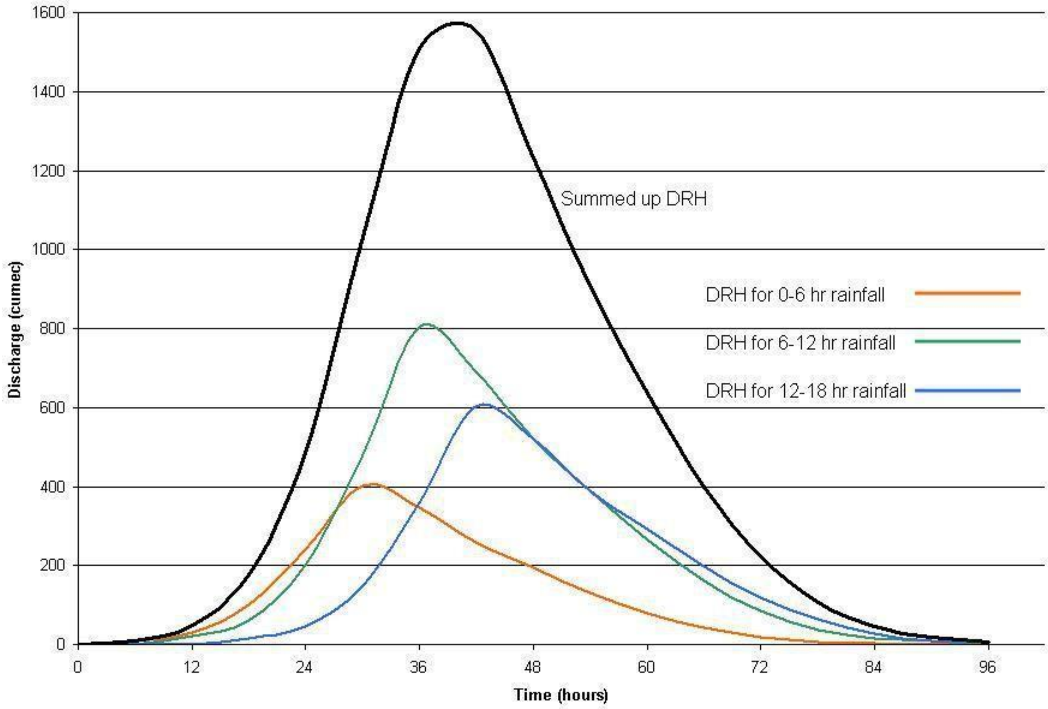


FIGURE 12. Final direct runoff hydrograph derived from summation of individual DRHs

The calculations to generate the direct runoff hydrograph (DRH) from a given

UH and ERH can be conveniently done using a spreadsheet program, like the Microsoft XL.

A sample calculation for the example solved graphically is given in the following table. Note the 6 hour shift of the DRHs in the second and subsequent hours.

Time (hours)	Unit Hydrograph ordinates (m^3/s)	Direct runoff due to 2 cm excess rainfall in first 6 hours (m^3/s) (I)	Direct runoff due to 4 cm excess rainfall in second 6 hours (m^3/s) (II)	Direct runoff due to 3 cm excess rainfall in third 6 hours (m^3/s) (III)	Direct runoff Hydrograph (m^3/s) (I)+(II)+(III)
0	0	0	0	0	0
6	5	10	0	0	10
12	15	30	20	0	50
18	50	100	60	15	175
24	120	240	200	45	485
30	201	402	480	150	1032
36	173	346	804	360	1510
42	130	260	692	603	1555
48	97	194	520	519	1233
54	66	132	388	390	910
60	40	80	264	291	635
66	21	42	160	198	400
72	9	18	84	120	222
78	3.5	7	36	63	106
84	2	4	14	27	45
90		0	8	10.5	18.5
96		0	0	6	6

The last column in the above table gives the ordinates of the DRH produced by the ERH. If the base flow is known or estimated (Lesson 2.2), then this should be added to the DRH to obtain the 6-houly ordinates of the flood hydrograph.

The S – curve

This is a concept of the application of a hypothetical storm of 1 cm ERH of infinite duration spread over the entire catchment uniformly. This may be done by shifting the UH by the T-duration for a large number of periods. The resulting hydrograph (a typical one is shown in Figure 13) is called the S – hydrograph, or the S – curve due to the summation of an infinite series of T-hour unit hydrographs spaced T – hour apart. For the example of the UH given in the earlier section, the table below provides the necessary calculations.

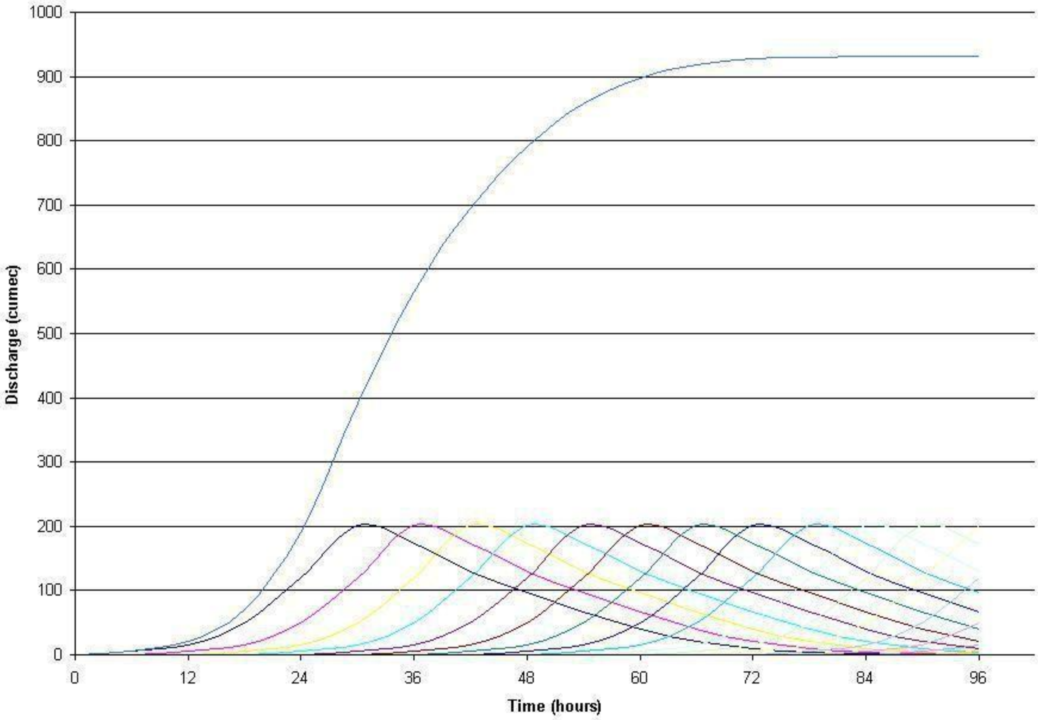


FIGURE 13. S - Curve, or Summed up Unit Hydrographs

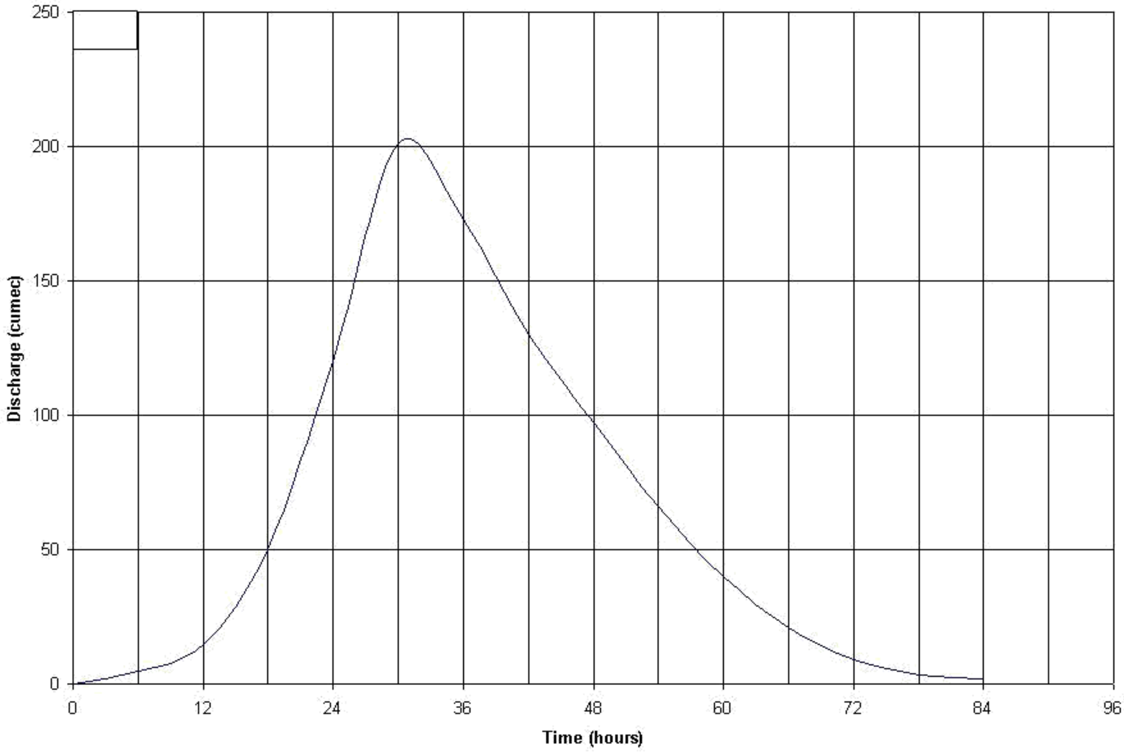


FIGURE 8. A 6-hour unit hydrograph

Time (hr)	UH Ordi-Nates	UH Ordi-nates shifted by 6 hr	UH Ordi-nates shifted by 12 hr	UH Ordi-nates shifted by 18 hr	UH Ordi-nates shifted by 24 hr	…	…	…	…	…	…	…	…	…	…	…	Sum of all the UH ordi-nates
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
12	15	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
18	50	15	5	0	0	0	0	0	0	0	0	0	0	0	0	0	70
24	120	50	15	5	0	0	0	0	0	0	0	0	0	0	0	0	190
30	201	120	50	15	5	0	0	0	0	0	0	0	0	0	0	0	391
36	173	201	120	50	15	5	0	0	0	0	0	0	0	0	0	0	564
42	130	173	201	120	50	15	5	0	0	0	0	0	0	0	0	0	694
48	97	130	173	201	120	50	15	5	0	0	0	0	0	0	0	0	791
54	66	97	130	173	201	120	50	15	5	0	0	0	0	0	0	0	857
60	40	66	97	130	173	201	120	50	15	5	0	0	0	0	0	0	897
66	21	40	66	97	130	173	201	120	50	15	5	0	0	0	0	0	918
72	9	21	40	66	97	130	173	201	120	50	15	5	0	0	0	0	927
78	3.5	9	21	40	66	97	130	173	201	120	50	15	5	0	0	0	930.5
84	2	3.5	9	21	40	66	97	130	173	201	120	50	15	5	0	0	932.5
90	0	2	3.5	9	21	40	66	97	130	173	201	120	50	15	5	0	932.5
96	0	0	2	3.5	9	21	40	66	97	130	173	201	120	50	15	5	932.5

The average intensity of the effective rainfall producing the S – curve is 1/T (mm/h) and the equilibrium discharge is given as $(\frac{A}{T} X10^{4}) m^3 / h$ where, A is the area of the catchment in Km^2 and T is the unit hydrograph duration in hours.

Application of the S – curve

Though the ***S – curve*** is a theoretical concept, it is an effective tool to derive a ***t – hour*** UH from a ***T – hour*** UH, when ***t*** is smaller than T or ***t*** is larger than T but not an exact multiple of T. In case ***t*** is a multiple of T, the corresponding

UH can be obtained without the aid of a S – hydrograph by summing up the required number of UH, lagged behind by consecutive T – hours.

For all other cases shift the original S – hydrograph as derived for the T – hour UH by ***t*** hours to obtain a lagged S- hydrograph. Subtract the ordinates of the second curve from the first to obtain the ***t*** – hour graph. Next, scale the ordinates of the discharge hydrograph by a factor ***t/T***, to obtain the actual ***t*** – hour UH which would result due to a total 1 cm of rainfall over the catchment.

This is illustrated by the S-curve derived in the previous section.

Recall that the S-curve was obtained from a 6-hour UH. Let us derive the UH for a 3-hour duration. Since we do not know the ordinates of the S-curve at every 3-hour interval, we interpolate and write them in a tabular form as given in the table below:

Time	S-curve ordinates as derived from 6-hr UH (I)	S-curve ordinates as derived from 6-hr UH but with inter-polated values (II)	S-curve ordinates as derived from 6-hr UH lagged by 3 hrs. (III)	Difference of the two S-curves (II) – (III) (IV)	3-hr UH ordinates Col. (IV) divided by (3hr/6hr) = (IV)*2
(hours)	(m^3/s)	(m^3/s)	(m^3/s)	(m^3/s)	(m^3/s)
0	0	0		0	
3		2.5	0	2.5	
6	5	5	2.5	2.5	
9		12.5	5	7.5	
12	20	20	12.5	7.5	
15		45	20	25	
18	70	70	45	25	
21		130	70	60	
24	190	190	130	60	
27		290.5	190	100.5	
30	391	391	290.5	100.5	

33		477.5	391	86.5	
36	564	564	477.5	86.5	
39		629	564	65	
42	694	694	629	65	
45		742.5	694	48.5	
48	791	791	742.5	48.5	
51		824	791	33	
54	857	857	824	33	
57		877	857	20	
60	897	897	877	20	
63		907.5	897	10.5	
66	918	918	907.5	10.5	
69		922.5	918	4.5	
72	927	927	922.5	4.5	
75		928.75	927	1.75	
78	930.5	930.5	928.75	1.75	
81		931.35	930.5	0.85	
84	932.5	932.5	931.35	1.15	
87		932.5	932.5	0	
90	932.5	932.5	932.5	0	
93		932.5	932.5	0	
96	932.5	932.5	932.5	0	

Derivation of unit hydrograph

An observed flood hydrograph at a streamflow gauging station could be a hydrograph resulting from an isolated intense short – duration storm of nearly uniform distribution in time and space, or it could be due to a complex rainfall event of varying intensities. In the former case, the observed hydrograph would mostly be single peaked whereas for the latter, the hydrograph could be multi peaked depending on the variation in the rainfall intensities. For the purpose of this course, we shall only consider rainfall to be more or less uniformly distributed in time and space for the purpose of demonstrating the derivation of unit hydrograph. The procedure may be broadly divided into the following steps:

1. Obtain as many rainfall records as possible for the study area to ensure that the amount and distribution of rainfall over the watershed is accurately known. Only those storms which are isolated events and with uniform spatial and temporal distribution are selected along with the observed hydrograph at the watershed outlet point.
2. Storms meeting the following criteria are generally preferred and selected out of the uniform storms data collected in Step 1.
3. Storms with rainfall duration of around 20 to 30 % of ***basin lag***,
4. Storms having rainfall excess between 1 cm and 4.5 cm.

5. From the observed total flood hydrograph for each storm separate the base flow and plot the direct runoff hydrograph.

6. Measure the total volume of water that has passed the flow measuring point by finding the area under the DRH curve. Since area of the watershed under consideration is known, calculate the average uniform rainfall depth that produced the DRH by dividing the volume of flow
(step 3) by the catchment area. This gives the effective rainfall (ER) corresponding to the storm. This procedure has to be repeated for each selected storm to obtain the respective ERs.

7. Express the hydrograph ordinate for each storm at T – hour is the duration of rainfall even. Divide each ordinate of the hydrograph by the respective storm ER to obtain the UH corresponding to each storm.

8. All UHs obtained from different storm events should be brought to the same duration by the S – curve method.

9. The final UH of specific duration is obtained by averaging the ordinates of he different UH obtained from step 6.

Unit hydrograph for ungauged catchments

For catchments with insufficient rainfall or corresponding concurrent runoff data, it is necessary to develop synthetic unit hydrograph. These are unit hydrographs constructed form basin characteristics. A number of methods like that of Snyder's had been used for the derivation of the Synthetic hydrographs. However, the present recommendations of the Central Water Commission discourage the use of the Snyder's method.

Instead, the Commission recommends the use of the Flood Estimation Reports brought out for the various ***sub–zones*** in deriving the unit hydrograph for the region. These sub–zones have been demarcated on the basis of similar hydro – meteorological conditions and a list of the basins may be found. The design flood is estimated by application of the design storm rainfall to the synthetic hydrograph developed by the methods outlined in the reports.

Catchment modelling

With the availability of personal computer high processing speed within easy reach of all, it is natural that efforts have been directed towards numerical modeling the catchment dynamics and its simulation. It is not possible to outline each model in detail, but the general concept followed is to represent each physical process by a conceptual mathematical model which can be represented by an equivalent differential or ordinary equation. These equations are solved by changing the equations to solvable form and writing algorithms in suitable computer language. However, the user of the programs generally input data through a ***Graphical User Interface*** (GUI) since there is a lot of spatial information to be included like land-use, land-cover, soil property, etc. Now a day, this information interaction between the user and the computer is through ***Geographic Information System*** (GIS) software.Once the information is processed, the output results are also displayed graphically.

Examples of catchment models

Though many of these models are sold commercially, there are quite a few developed by academic institutions and government agencies worldwide which are free and can be downloaded for non – commercial purposes through the internet. A few examples are given below.

- US Army corps of Engineers' ***HEC-HMS*** and ***HEC-GeoHMS***
- US Army corps of Engineers' ***GRASS***
- US Army corps of Engineers' ***TOPMODEL***

Water resources section of the Department of Civil Engineering, IIT Kharagpur has developed a watershed simulation model based on deterministic theory. A copy of the same may be made available on request for educational purposes.

Important terms

1. ***Linearity*****:** A linear relation between rainfall and runoff form a catchment suggests that variations in rainfall over a catchment is related to the variations in runoff from the outlet of the catchment by a linear function.

2. ***Basin lag*****:** Basin lag is the time between the peak flow and the centroid of rainfall.

3. ***Graphical User Interface*** **(GUI):** An interface that represents programs, files, and options with graphical images is called GUI. These images can include icons, menus, and dialog boxes. The user selects and activates these options by pointing and clicking with a mouse or with the keyboard. A particular GUI item (for example, a scroll bar) works the same way in all applications.

4. ***Geographic Information System (GIS):*** A system, usually computer based, for the input, storage, retrieval, analysis and display of interpreted geographic data. The database is typically composed of map-like spatial representations, often called coverages or layers. These layers may involve a three-dimensional matrix of time, location, and attribute or activity. A GIS may include digital line graph (DLG) data, Digital Elevation Models (DEM), geographic names, land-use characterizations, land ownership, land cover, registered satellite and/or areal photography along with any other associated or derived geographic data.

5. ***HEC-HMS*****:** The Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

6. ***HEC-GeoHMS*:** The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) is a public-domain software package for use with the ArcView Geographic Information System. GeoHMS uses ArcView and Spatial Analyst to develop a number of hydrologic modeling inputs. Analyzing the digital terrain information, HEC-GeoHMS transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. In addition to the hydrologic data structure, capabilities include the development of grid-based data for linear quasi-distributed runoff transformation (ModClark), HEC-HMS basin model, physical watershed and stream characteristics, and background map file.

7. ***GRASS*:** GRASS is an integrated set of programs designed to provide digitizing, image processing, map production, and geographic information system capabilities to its users. GRASS is open software with freely available source code written in C.

8. ***Topmodel*:** TOPMODEL predicts catchment water discharge and spatial soil water saturation pattern based on precipitation and evapotranspiration time series and topographic information.

UNIT-III

GROUND WATER OCCURANCE

Introduction

In the earlier lesson, qualitative assessment of subsurface water whether in the unsaturated or in the saturated ground was made. Movement of water stored in the saturated soil or fractured bed rock, also called aquifer, was seen to depend upon the hydraulic gradient. Other relationships between the water storage and the portion of that which can be withdrawn from an aquifer were also discussed.

In this lesson, we derive the mathematical description of saturated ground water flow and its exact and approximate relations to the hydraulic gradient.

Although ground water flow is three – dimensional phenomenon, it is easier to analyse flows in two – dimension. Also, as far as interaction between surface water body and ground water is concerned, it is similar for lakes, river and any such body. Here we qualitatively discuss the flow of ground water through a few examples which show the relative interaction between the flow and the geological properties of the porous medium. Here, the two – dimensional plane is assumed to be vertical.

1. Example of a gaining lake and river.

Figure 11 shows an example of a lake perched on a hill that is receiving water from the adjacent hill masses. It also shows a river down in a valley, which is also receiving water.

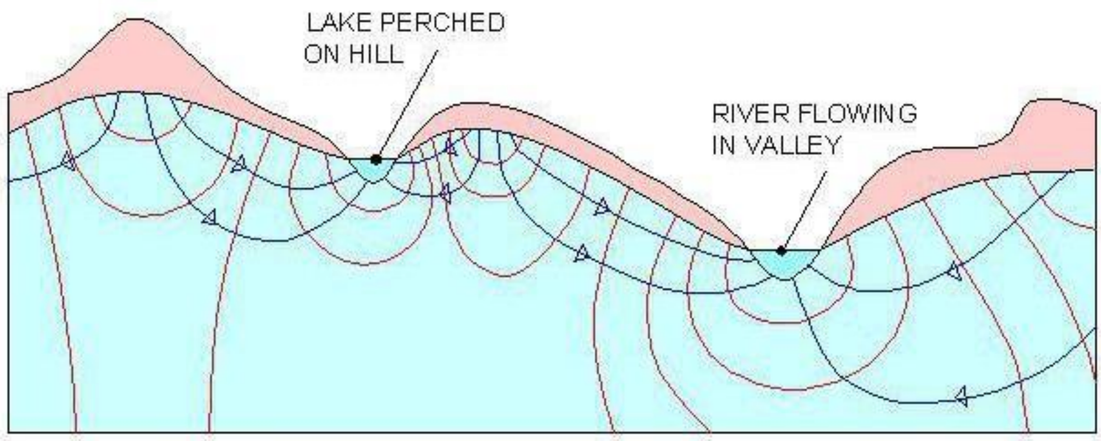


FIGURE 11. Example of a lake and a river, both of which are receiving warer from the adjoining soils.

2. Example of a partially losing lake, a disconnected losing lake, and a gaining river.

Figure 12 illustrates this example modifies the situation of example 1 slightly.

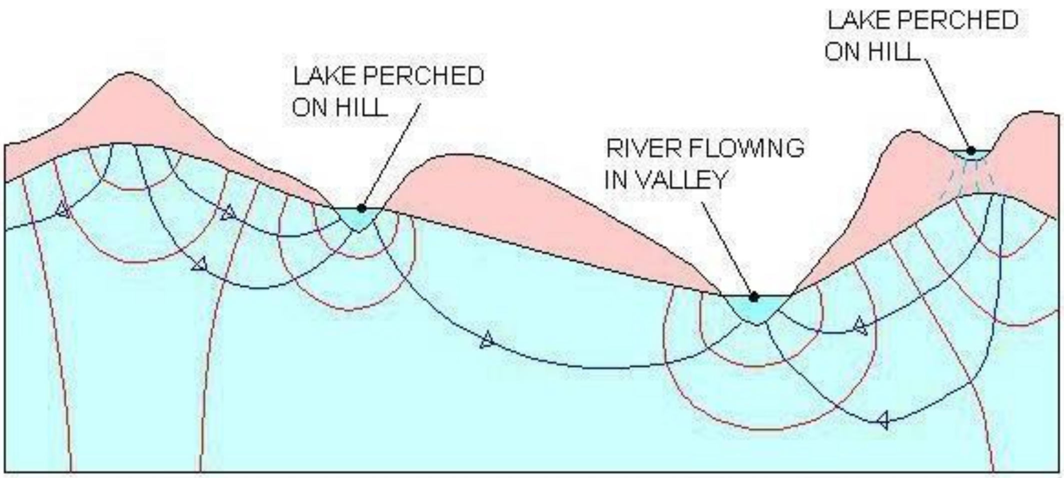


FIGURE 12. An example of two lakes, one of which is gaining water, as well as loosing; one river that is continuously gaining; and another lake perched on a hill, disconnected from the water table, and thus loosing water by infiltration

3. Example of flow through a heterogeneous media, case I.

This case (Figure 13) illustrates the possible flow through a sub-soil material of low hydraulic conductivity sandwiched between materials of relatively higher hydraulic conductivities.

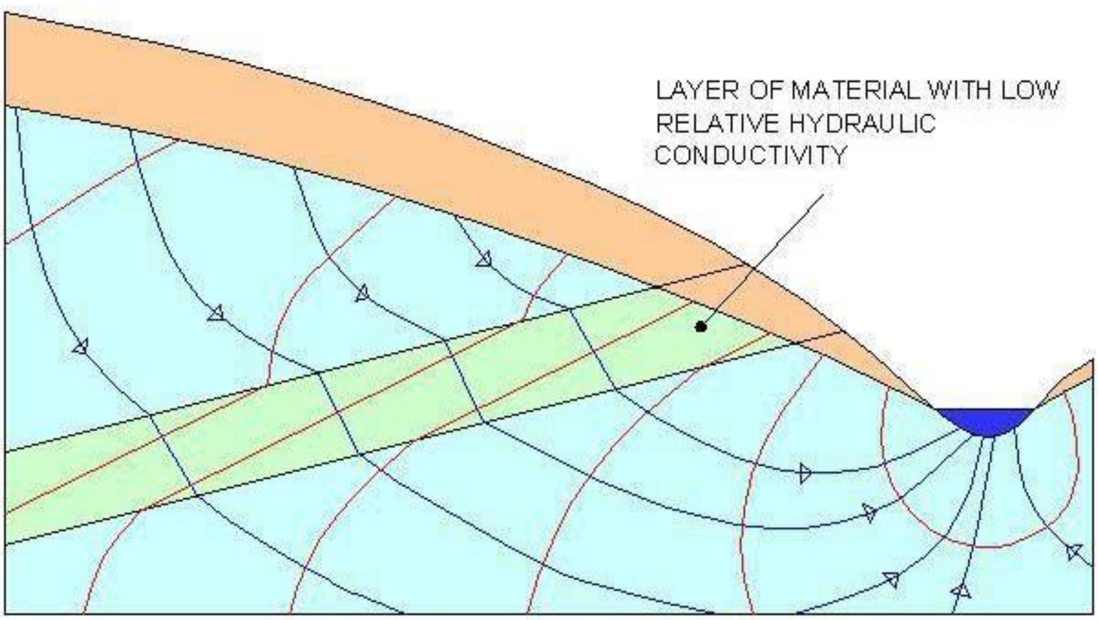


FIGURE 13. Example of sub-soil flow through heterogeneous media - Case I

4. Example of flow through a heterogeneous media, case II.

This case (Figure 14) is just opposite to that shown in example 3. Here, the flow is through a sub-soil material of high hydraulic conductivity sandwiched between materials of relatively low hydraulic conductivities.

Water table contours and regional flow

For a region, like a watershed, if we plot (in a horizontal plane) contours of equal hydraulic head of the ground water, then we can analyse the movement of ground water in a regional scale. Figure 15 illustrates the concept, assuming homogeneous porous media in the region for varying degrees of hydraulic conductivity (which is but natural for a real setting).

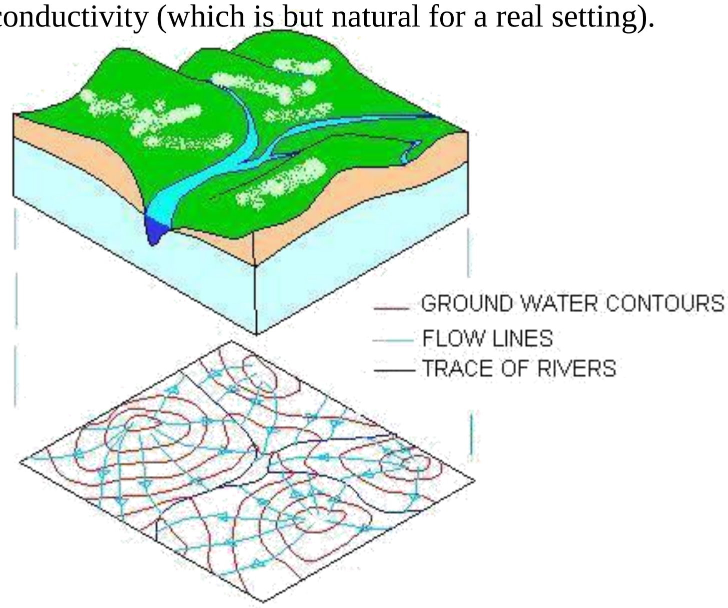


FIGURE 15. Movement of ground water in a regional scale

Aquifer properties and ground water flow

Porosity

Ground water is stored only within the pore spaces of soils or in the joints and fractures of rock which act as a aquifers. The porosity of an earth material is the percentage of the rock or soil that is void of material. It is defined mathematically by the equation

$$n = \frac{100 v_v}{v} \qquad (2)$$

Where n is the porosity, expressed as percentage; v_v is the volume of void space in a unit volume of earth material; and v is the unit volume of earth material, including both voids and solid.

Specific Yield

While porosity is a measure of the water bearing capacity of the formation, all this water cannot be drained by gravity or by pumping from wells, as a portion of the water is held in the void spaces by molecular and surface tension forces. If gravity exerts a stress on a film of water surrounding a mineral grain (forming the soil), some of the film will pull away and drip downward. The remaining film will be thinner, with a greater surface tension so that, eventually, the stress of gravity will be exactly balanced by the surface tension (Hygroscopic water is the moisture clinging to the soil particles because of surface tension). Considering the above phenomena, the Specific Yield (S_y) is the ratio of the volume of water that drains from a saturated soil or rock owing to the attraction of gravity to the total volume of the aquifer.

If two samples are equivalent with regard to porosity, but the average grain size of one is much smaller than the other, the surface area of the finer sample will be larger. As a result, more water can be held as hygroscopic moisture by the finer grains.

The volume of water retained by molecular and surface tension forces, against the force of gravity, expressed as a percentage of the volume of the saturated sample of the aquifer, is called Specific Retention S_r, and corresponds to what is called the Field Capacity.

Hence, the following relation holds good:

$$n = S_y + S_r \qquad (3)$$

Specific storage (s_s)

Specific storage (s_s), also sometimes called the Elastic Storage Coefficient, is the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water per unit change in potentiometric head. Specific Storage is given by the expression

$$S_s = \gamma\left(\alpha + n\beta\right) \qquad (4)$$

where γ is the unit weight of water, α is the compressibility of the aquifer skeleton; *n* is the porosity; β is the compressibility of water.

Specific storage has the dimensions of length^{-1}

The storativity (S) of a confined aquifer is the product of the specific storage (S_s) and the aquifer thickness (b).

$$S = bS_s \qquad (5)$$

All of the water released is accounted for by the compressibility of the mineral skeleton and pore water. The water comes from the entire thickness of the aquifer.

In an unconfined aquifer, the level of saturation rises or falls with changes in the amount of water in storage. As water level falls, water drains out from the pore spaces. This storage or release due to the specific yield (Sy) of the aquifer. For an unconfined aquifer, therefore, the storativity is found by the formula.

$$S = S_y + hS_s \qquad (6)$$

Where h is the thickness of the saturated zone.

Since the value of Sy is several orders of magnitude greater than hSs for an unconfined aquifer, the storativity is usually taken to be equal to the specific yield.

Aquifers and confining layers

It is natural to find the natural geologic formation of a region with varying degrees of hydraulic conductivities. The permeable materials have resulted usually due to weathering, fracturing and solution effects from the parent bed rock. Hence, the physical size of the soil grains or the pre sizes of fractured rock affect the movement of ground water flow to a great degree. Based on these, certain terms that have been used frequently in studying hydrogeology, are discussed here.

- **Aquifer:** This is a geologic unit that can store and transmit water at rates fast enough to supply reasonable amount to wells.

- **Confining layers:** This is a geologic unit having very little hydraulic conductivity.
- Confining layers are further subdivided as follows:
- **Aquifuge**: an absolutely impermeable layer that will not transmit any water.
- Aquitard: A layer of low permeability that can store ground water and also transmit slowly from one aquifer to another. Also termed as “leaky aquifer’.
- **Aquiclude**: A unit of low permeability, but is located so that it forms an upper or lower boundary to a ground water flow system.

Aquifers which occur below land surface extending up to a depth are known as unconfined. Some aquifers are located much below the land surface, overlain by a confining layer. Such aquifers are called confined or artesian aquifers. In these aquifers, the water is under pressure and there is no free water surface like the water table of unconfined aquifer.

Continuity equation and Darcy’s law under steady state conditions

Consider the flow of ground water taking place within a small cube (of lengths Δx, Δy and Δz respectively the direction of the three areas which may also be called the elementary control volume) of a saturated aquifer as shown in Figure 1.

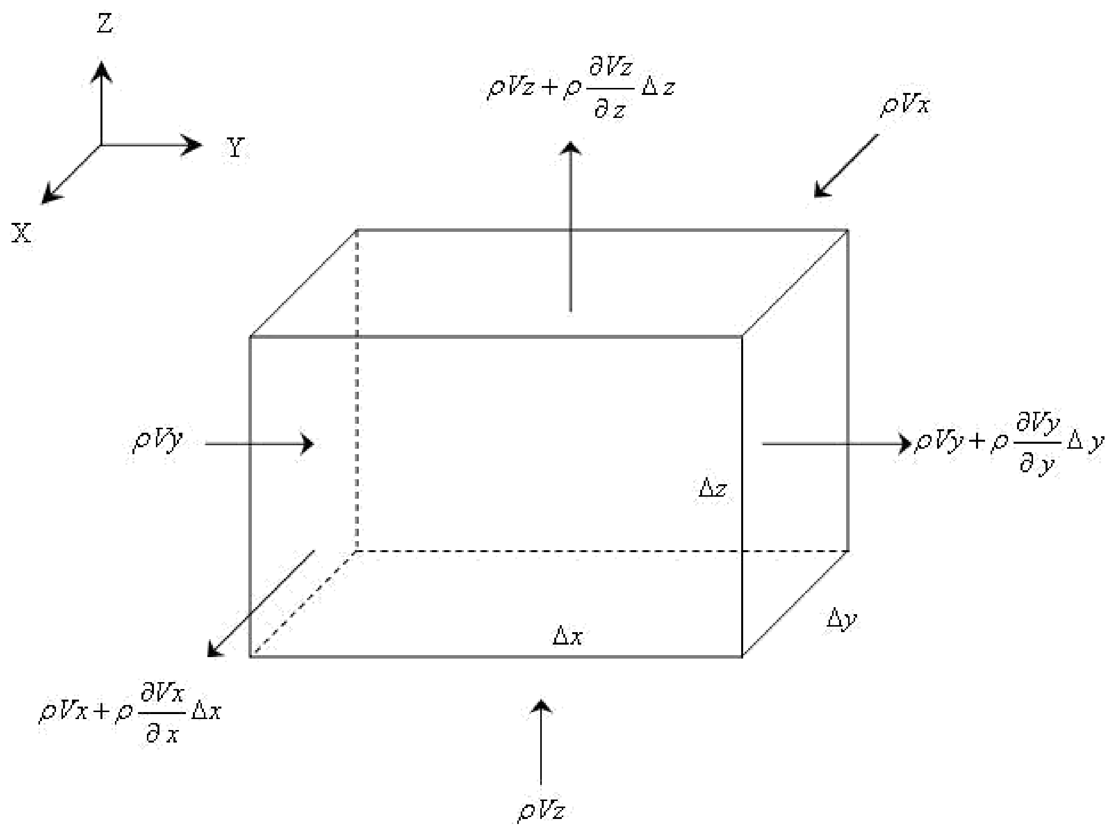


FIGURE 1. Infinitesimal cube for deriving the equation of continuity of flow of ground water

It is assumed that the density of water (ρ) does not change in space along the three directions which implies that water is considered incompressible. The velocity components in the x, y and z directions have been denoted as v_x, v_y, v_z respectively.

Since water has been considered incompressible, the total incoming water in the cuboidal volume should be equal to that going out. Defining inflows and outflows as:

Inflows:

In x-direction: $\rho\ v_x\ (\Delta y.\Delta x)$ In y-direction: $\rho\ v_y\ (\Delta x.\Delta z)$ In z-direction: $\rho\ v_z\ (\Delta x.\Delta y)$

This is continuity equation for flow. But this water flow, as we learnt in the previous lesson, is due to a difference in potentiometric head per unit length in the direction of flow. A relation between the velocity and potentiometric gradient was first suggested by Henry Darcy, a French Engineer, in the mid nineteenth century.

He found experimentally (see figure below) that the discharge 'Q' passing through a tube of cross sectional area 'A' filled with a porous material is proportional to the difference of the hydraulic head 'h' between the two end points and inversely proportional to the flow length'L'.

It may be noted that the total energy (also called head, h) at any point in the ground water flow per unit weight is given as

$$h = Z + \frac{p}{\gamma} + \frac{v^2}{2g} \quad (3)$$

Where

Z is the elevation of the point above a chosen datum;

$h = Z + \frac{p}{\gamma}$ is termed as the potentiometric head (or piezometric head in some texts)

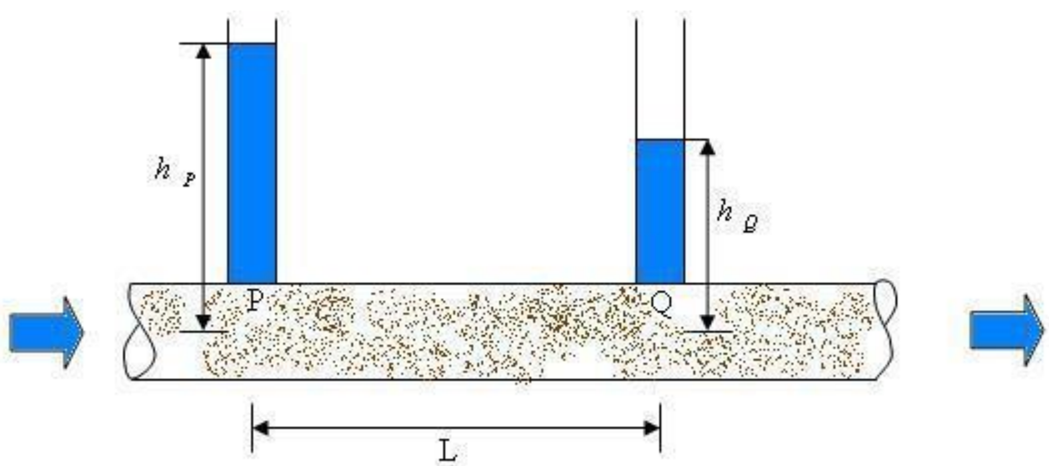


FIGURE 2. Flow through a saturated porous medium

The coefficient 'K' has dimensions of L/T, or velocity, and as seen in the last lesson this is termed as the hydraulic conductivity.

Thus the velocity of fluid flow would be:

$$v = \frac{Q}{A} = -K\left(\frac{dh}{Dl}\right) \qquad (7)$$

It may be noted that this velocity is not quite the same as the velocity of water flowing through an open pipe. In an open pipe, the entire cross section of the pipe conveys water. On the other hand, if the pipe is filed with a porous material, say sand, then the water can only flow through the pores of the sand particles.

Hence, the velocity obtained by the above expression is only an apparent velocity, with the actual velocity of the fluid particles through the voids of the porous material is many time more. But for our analysis of substituting the expression for velocity in the three directions x, y and z in the continuity relation, equation (2) and considering each velocity term to be proportional to the hydraulic gradient in the corresponding direction, one obtains the following relation

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = 0 \qquad (8)$$

Here, the hydraulic conductivities in the three directions (K_x, K_y and K_z) have been assumed to be different as for a general anisotropic medium. Considering isotropic medium with a constant hydraulic conductivity in all directions, the continuity equation simplifies to the following expression:

$$\frac{\partial^2 h}{\partial x} + \frac{\partial^2 h}{\partial y} + \frac{\partial^2 h}{\partial z} = 0 \qquad (9)$$

In the above equation, it is assumed that the hydraulic head is not changing with time, that is, a steady state is prevailing. If now it is assumed that the potentiometric head changes with time at the location of the control volume, then there would be a corresponding change in the ***porosity*** of the aquifer even if the fluid density is assumed to be unchanged.

Important term:

Porosity: It is ratio of volume of voids to the total volume of the soil and is generally expressed as percentage.

Steady one dimensional flow in aquifers

Some simplified cases of ground water flow, usually in the vertical plane, can be approximated by one dimensional equation which can then be solved analytically. We consider the confined and unconfined aquifers separately, in the following sections.

Confined aquifers

If there is a steady movement of ground water in a confined aquifer, there will be a gradient or slope to the potentiometric surface of the aquifer. The gradient, again, would be decreasing in the direction of flow. For flow of this type, Darcy's law may be used directly.

Aquifer with constant thickness

This situation may be shown as in Figure 6.

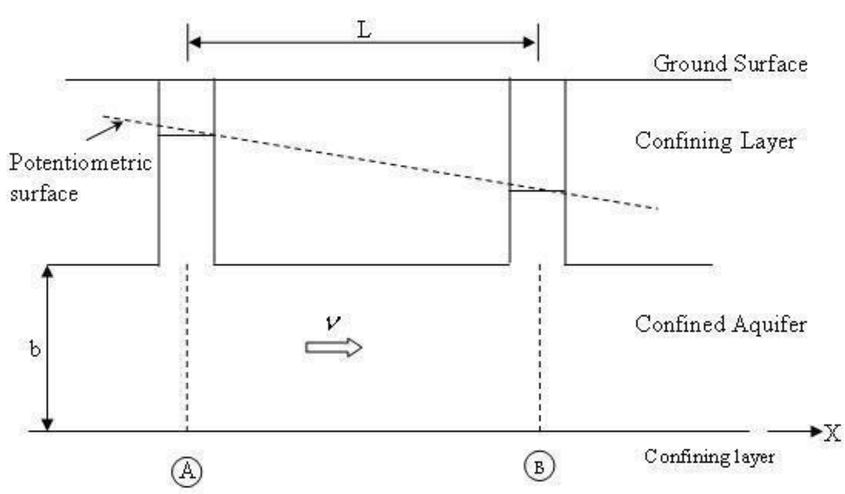


FIGURE 6. Flow through an aquifer of constant thckness

Assuming unit thickness in the direction perpendicular to the plane of the paper, the flow rate ‘q’ (per unit width) would be expressed for an aquifer of thickness’b’

$$q = b * 1 * v \qquad (43)$$

According to Darcy’s law, the velocity ‘v’ is given by

$$v = -K \frac{\partial h}{\partial x} \qquad (44)$$

Where h, the potentiometric head, is measured above a convenient datum. Note that the actual value of ’h’ is not required, but only its gradient $\frac{\partial h}{\partial x}$ in the direction of flow, x, is what matters. Here is K is the hydraulic conductivity

Hence,

$$q = b K \frac{\partial h}{\partial x} \qquad (45)$$

The partial derivative of ‘h’ with respect to ‘x’ may be written as normal derivative since we are assuming no variation of ‘h’ in the direction normal to the paper. Thus

$$q = - b K \frac{dh}{dx} \qquad (46)$$

For steady flow, q should not vary with time, t, or spatial coordinate, x. hence,

$$\frac{dq}{dx} = -bK \frac{d^2 h}{dx^2} = 0 \qquad (47)$$

Since the width, b, and hydraulic conductivity, K, of the aquifer are assumed to be constants, the above equation simplifies to:

$$\frac{d^2 h}{d x^2} = 0 \qquad (48)$$

Which may be analytically solved as

$$h = C_1 x + C_2 \qquad (49)$$

Selecting the origin of coordinate x at the location of well A (as shown in Figure 6), and having a hydraulic head, h_A and also assuming a hydraulic head of well B, located at a distance L from well A in the x-direction and having a hydraulic head h_B, we have:

$$h_A = C_1.0+C_2 \text{ and } h_B = C_1.L+C_2$$

Giving

$$C_1 = h - h_A /L \text{ and } C_2= h_A \qquad (50)$$

Thus the analytical solution for the hydraulic head 'h' becomes:

$$H = \frac{h_B - h_A}{L} x + h_A \qquad (51)$$

Aquifer with variable thickness

Consider a situation of one- dimensional flow in a confined aquifer whose thickness, b, varies in the direction of flow, x, in a linear fashion as shown in Figure 7.

The unit discharge, q, is now given as

$$q = - b(x) K \frac{dh}{dx} \qquad (52)$$

Where K is the hydraulic conductivity and dh/dx is the gradient of the potentiometric surface in the direction of flow,x.

$$b\frac{d^2h}{dx^2} + b'\frac{dh}{dx} = 0 \qquad (54)$$

A solution of the above differential equation may be found out which may be substituted for known values of the potentiometric heads h_A and h_B in the two observation wells A and B respectively in order to find out the constants of integration.

Unconfined aquifers

In an unconfined aquifer, the saturated flow thickness, h is the same as the hydraulic head at any location, as seen from Figure 8:

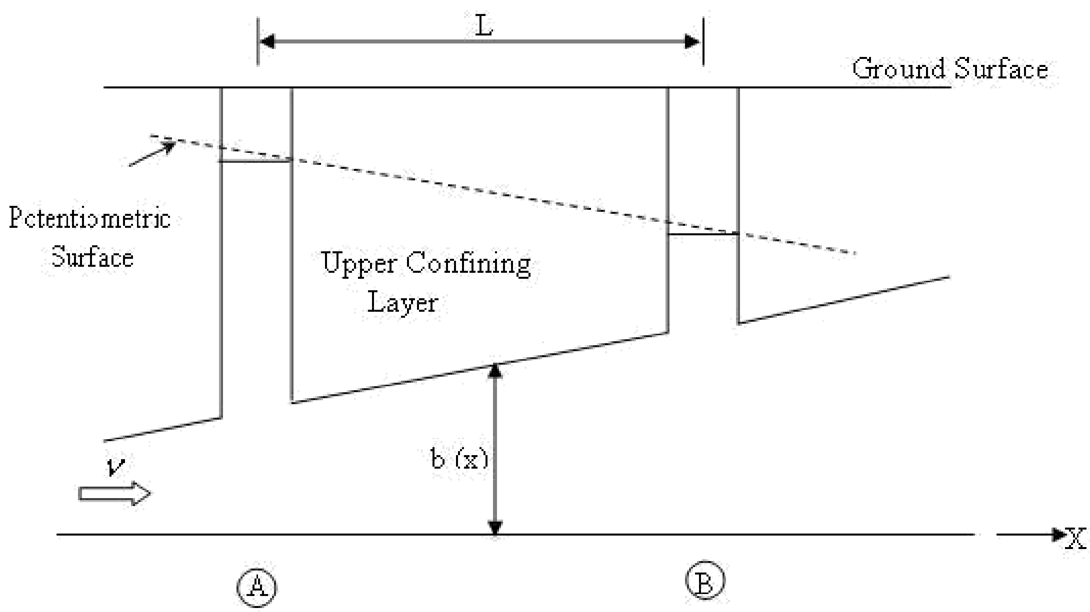


FIGURE 7. Flow through an aquifer with variable thickness

Considering no recharge of water from top, the flow takes place in the direction of fall of the hydraulic head, h, which is a function of the coordinate, x taken in the flow direction. The flow velocity, v, would be lesser at location A and higher at B since the saturated flow thickness decreases. Hence v is also a function of x and increases in the direction of flow. Since, v, according to Darcy's law is shown to be

$$v = K\frac{dh}{dx} \qquad (55)$$

the gradient of potentiometric surface, dh/dx, would (in proportion to the velocities) be smaller at location A and steeper at location B. Hence the gradient of water table in unconfined flow is not constant, it increases in the direction of flow.

This problem was solved by J.Dupuit, a French hydraulician, and published in 1863 and his assumptions for a flow in an unconfined aquifer is used to approximate the flow situation called Dupuit flow. The assumptions made by

Dupuit are:

5. The hydraulic gradient is equal to the slope of the water table, and
5. For small water table gradients, the flow-lines are horizontal and the equipotential lines are vertical.

The second assumption is illustrated in Figure 9.

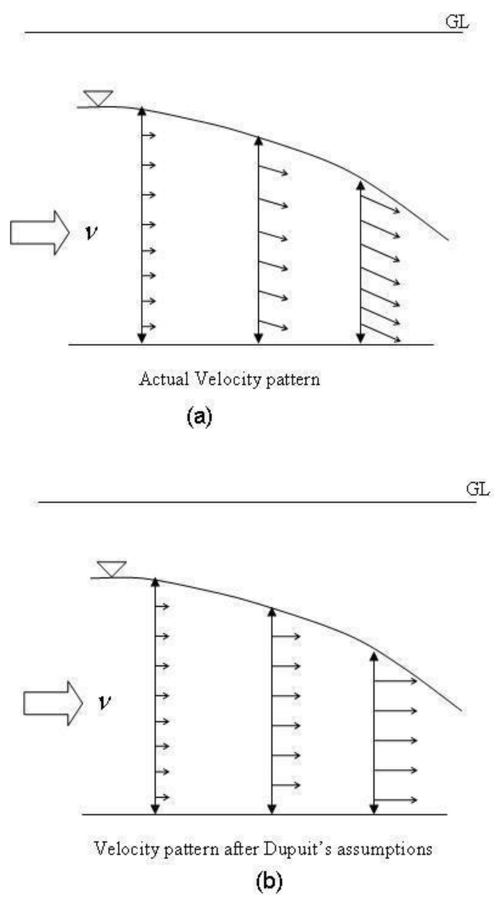


FIGURE 9. (a) Actual velocity pattern in ground water flow and
(b) Assumption of Dupuit regarding ground water flow

Solutions based on the Dupuit's assumptions have proved to be very useful in many practical purposes. However, the Dupuit assumption do not allow for a ***seepage face*** above an outflow side.

An analytical solution to the flow would be obtained by using the Darcy equation to express the velocity, v, at any point, x, with a corresponding hydraulic gradient

$$v = -K \frac{dh}{dx} \qquad (56)$$

Thus, the unit discharge, q, is calculated to be

$$q = -K h \frac{dh}{dx} \qquad (57)$$

Considering the origin of the coordinate x at location A where the hydraulic head us h_A and knowing the hydraulic head h_B at a location B, situated at a distance L from A, we may integrate the above differential equation as:

$$\int_0^L q \, dx = -K \int_{h_A}^{h_B} h \, dh \qquad (58)$$

Which, on integration, leads to

$$q x \Big|_0^L = -K \cdot \frac{h^2}{2} \Bigg|_{h_A}^{h_B} \qquad (59)$$

Or,

$$q \cdot L = K \left(\frac{h_A^2}{2} - \frac{h_B^2}{2} \right) \qquad (60)$$

Rearrangement of above terms leads to, what is known as the Dupuit equation:

$$q = -\frac{1}{2} K \frac{h_B^2 - h_A^2}{L} \qquad (61)$$

An example of the application of the above equation may be for the ground water flow in a strip of land located between two water bodies with different water surface elevations, as in Figure 10.

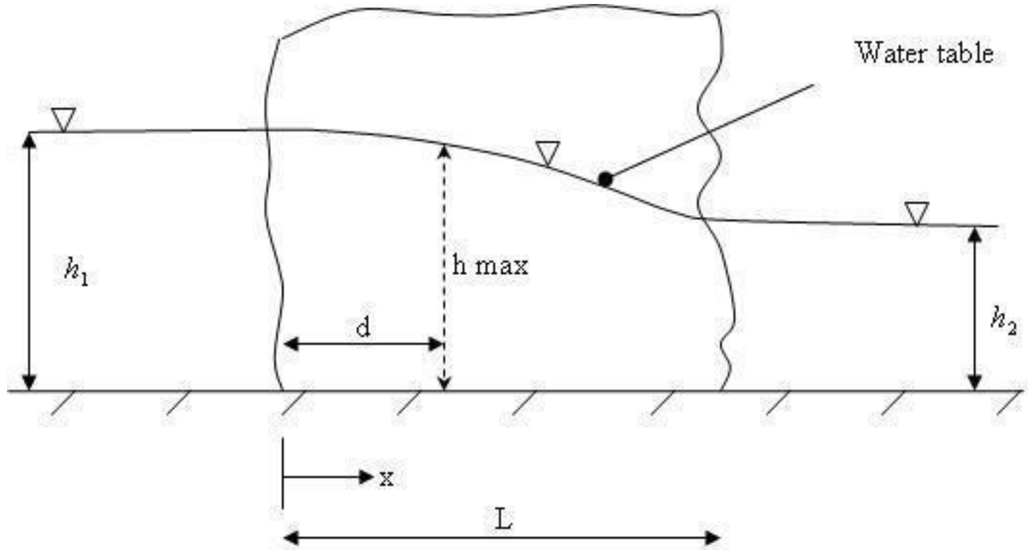


FIGURE 10. Ground water flow through a strip of land with difference in water surface elevation on either side.

The equation for the water table, also called the phreatic surface may be derived from Equation (61) as follows:

$$h = \sqrt{h_1^2 - (h_1^2 - h_2^2)\frac{x}{L}} \qquad (62)$$

In case of recharge due to a constant infiltration of water from above the water table rises to a many as shown in Figure 11:

There is a difference with the earlier cases, as the flow per unit width, q, would be increasing in the direction of flow due to addition of water from above. The flow may be analysed by considering a small portion of flow domain as shown in Figure 12.

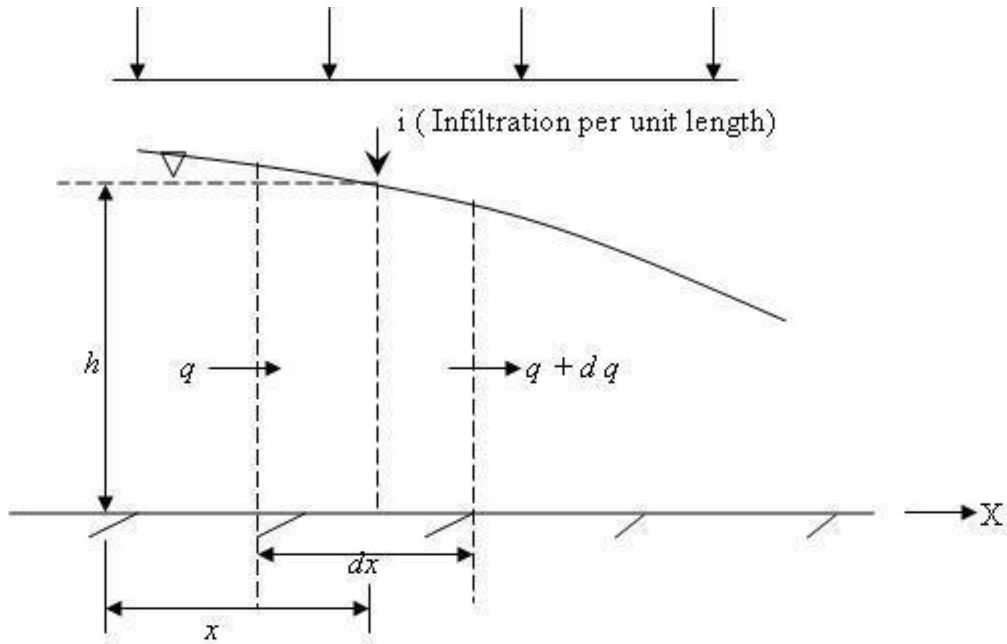


FIGURE 12. Definition of terms for flow analysis for the case shown in Figure 11

Considering the infiltration of water from above at a rate *i* per unit length in the direction of ground water flow, the change in unit discharge *dq* is seen to be

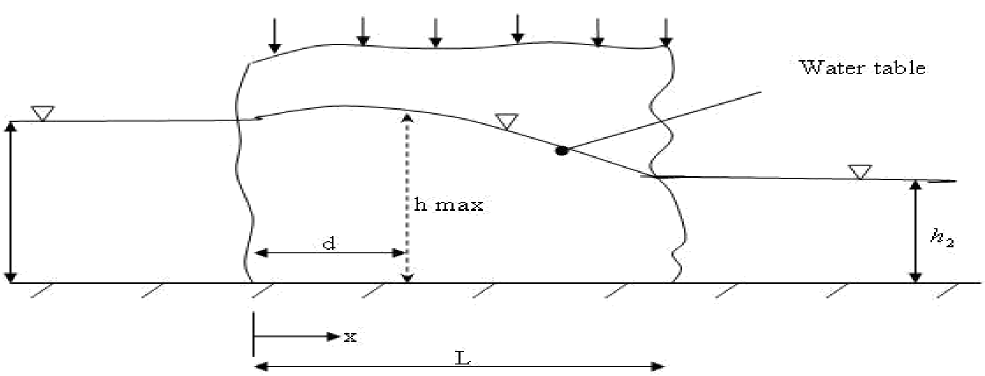


FIGURE 11. Ground water flow through a strip of land with infiltration from above

$$q_x = q_0 + 2x$$

Where q_0 is the unit discharge at the left boundary, $x = 0$, and may be found out to be

$$q_0 = \frac{(h_1^2 - h_1^2)}{2L} - \frac{iL}{2}$$

Which gives an expression for unit discharge q_x at any point x from the origin as

$$q_x = K\frac{(h_1^2 - h_1^2)}{2L} - i\left(\frac{L}{2} - x\right)$$

For no recharge due to infiltration, $i = 0$ and the expression for q_x is then seen to become independent of x, hence constant, which is expected.

WELLS

A well is an intake structure dug on the ground to draw water from the reservoirs of water stored within. The water from the well could be used to meet domestic, agricultural, industrial, or other uses. The structure may be an open dug well, or as is common these days, may be tube-wells. The well may be shallow, tapping an unconfined reservoir or could be deep, penetrating further inside the ground to tap a confined aquifer located within aquicludes. In this lesson, we shall discuss the design of tube wells, a typical installation of which is given in Figure 11.

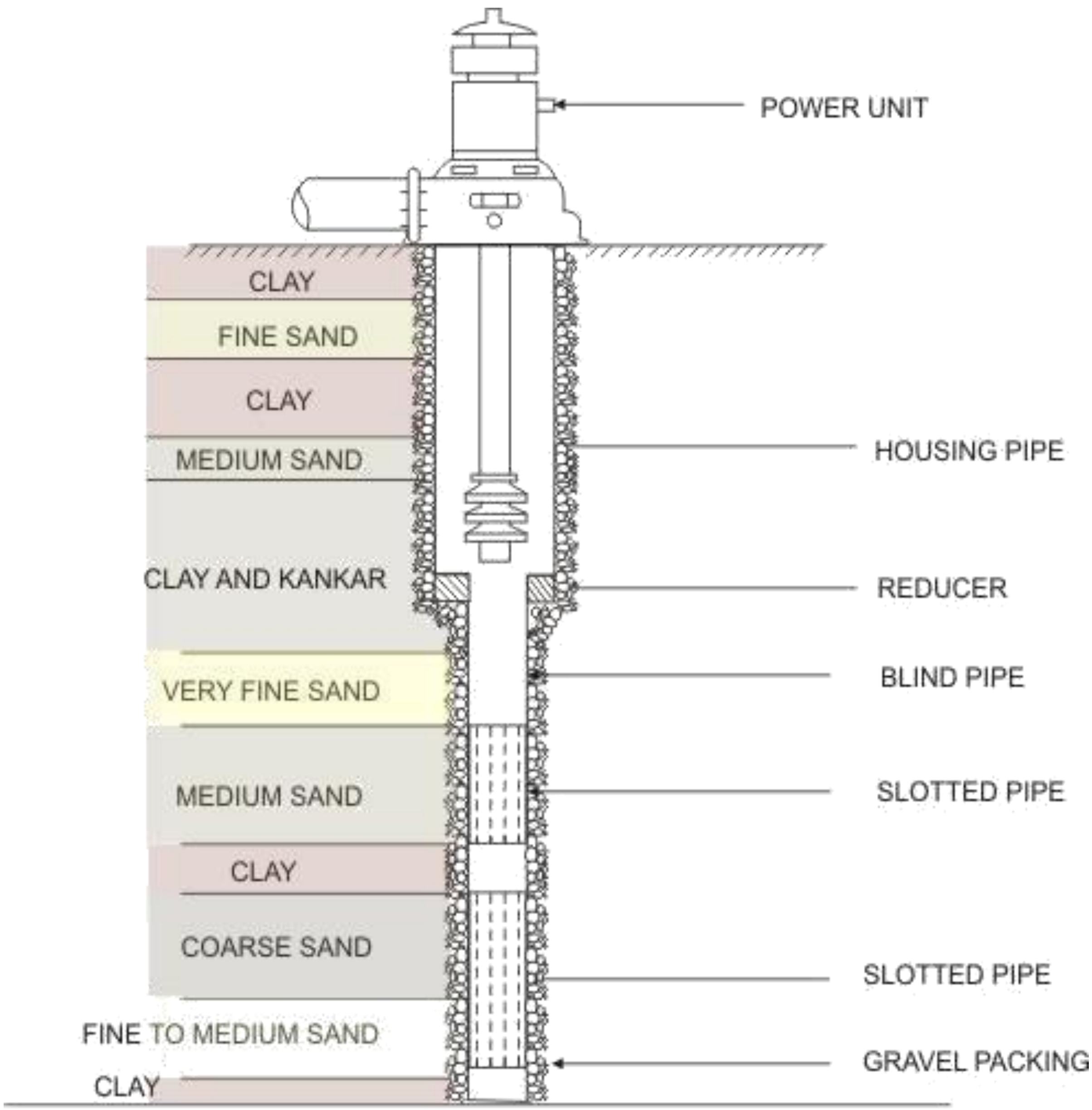


FIGURE . 11 TYPICAL INSTALLATION OF TUBE WELL

Design of a well involves selecting appropriate dimensions of various components and choosing proper materials to be used for its construction. A good design of tube well should aim at efficient utilisation of the aquifer, which it is supposed to tap, have a long and useful life, should have a low initial cost, and low mantenace and operation cost.

The parameters that need to be designed for a well include the following:

3. diameter
   The diameter of the well must be chosen to give the desired percentage of open area in the screen (15 to 18 percent) so that the entrance velocities near the screen do no exceed 3 to 6 cm/s so as to reduce the well losses and hence, the draw down. The velocity should be reasonably low as indicated, such that the five particles within the sand should not migrate towards the well strainer slots.

4. Well depth

5. Selection of strata to be tapped
   The samples during drilling are collected from various depths and a bore log is prepared. This log describes the soil material type, size distribution, uniformity coefficient etc. for the material available at different depths.

6. Well screen design
   This includes fixing the following parameters for a well: o
   Well screen length
   Well-screen slot size
   Well-screendiameter
   Well-screen material

In case of unconfined aquifers, where too thick and homogeneous aquifer is met, it is desirable to provide screen in the lower one third thickness. In case of confined aquifers where thick and nearly homogeneous aquifer is met, about 80 to 90 percent of the depth at the centre of the aquifer is advised to be screened. Where too thick and homogeneous aquifers are encountered it is common practice to place screen opposite the more permeable beds leaving about 0.3m depth both at the top and bottom of the aquifer, so that finer material in the transition zone does not move into the well.

The size of the well screen slots depends upon the gradation, and size of the formation material, so that there is no migration of fines near the slots. In case of naturally developed wells the slot size is taken as around 40 to 70 percent of the size of the formation material. If the slot size selected on this basis comes to less than 0.75 mm, then an artificial ground pack is used. An artificial gravel pack is required when the aquifer material is homogeneous with a uniformity coefficient less than 3 and effective grain size less than 0.25 mm.

The screen diameter is determined so that the entrance velocity near the well screen does not exceed 3 to 6 cm/sec.

The screen material should be resistant to incrustation and corrosion and should have the strength to withstand the weight of the well pipe. The selection of the screen material also depends on the quality of ground water, diameter and depth of the well and type of strata encountered.

Installation of tube wells

The entire process of installation of tube wells include drilling of a hole, installing the screen and housing pipes, gravel packing and development of the well to insure sand free water. Depending on the size of the tubewell, depth and formation to be drilled, available facility and technical know-how, different methods are used for the construction of tubewells. Two methods that are commonly used are explained below.

- *Cable-tool percussion drilling*
  A rig consists of a mast, lines of hoist for operating the drilling tool and a sand pump (Figure 12).

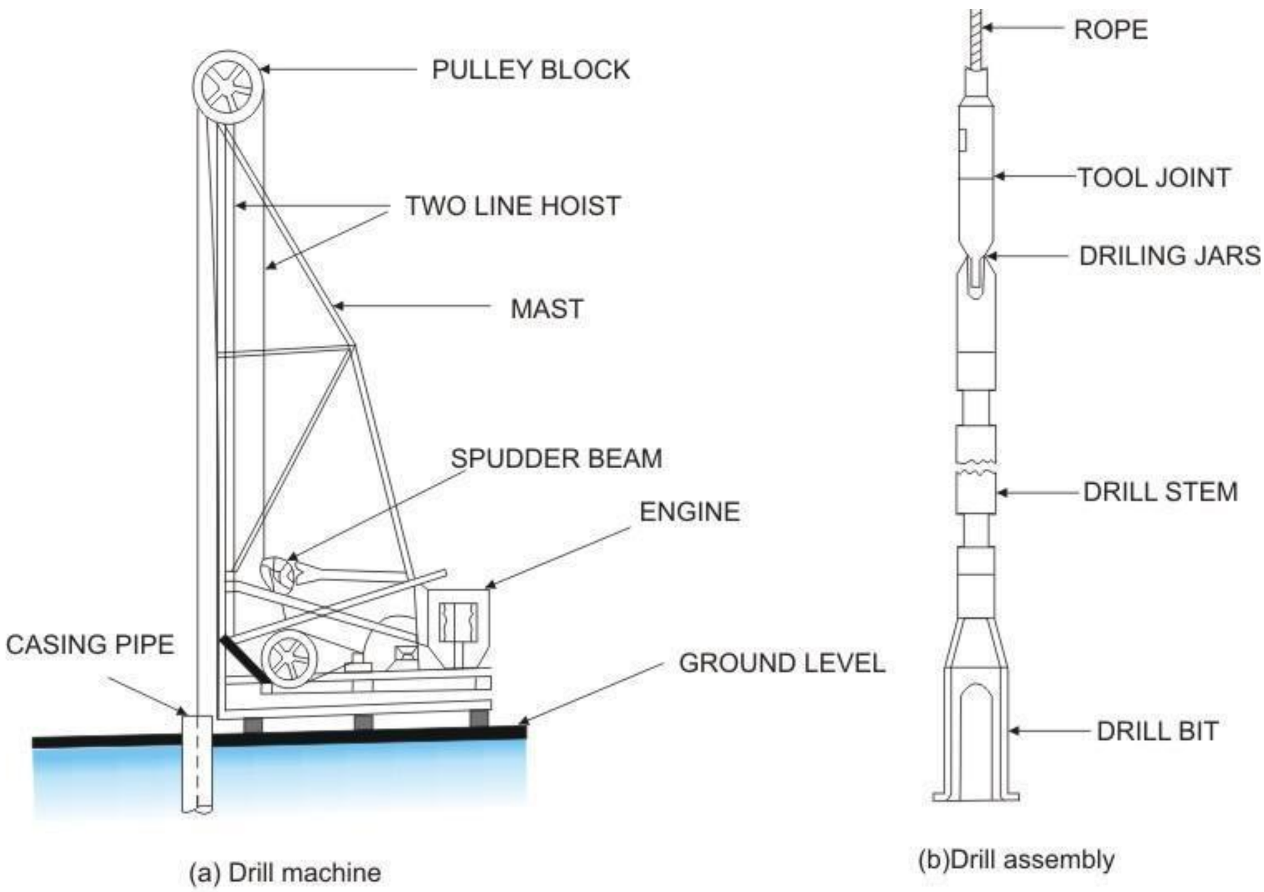


FIGURE .12 CABLE TOOL PERCUSSION DRILLING

The cutting tool is suspended from a cable and the drilling is accomplished by up and down movement (percussion) of the tool. A full string of drilling tool consists of four components:

1. Drill bit
2. Drill stem
3. Drilling jars
4. Rope socket

The drill bit is used to loosen the formation material and its reciprocating action breaks it down to smaller particles or muck. Water injected from the top converts the muck into slurry. For this purpose water is added as long as drilling continues in dry formations. The slurry flows up due to the pressure of water. The drill stem fixed just above the bit provides additional tools in order to maintain a straight line. The drilling jars consist of a pair of linked steel bars and can be moved in a vertical direction relative to each other. The rope socket connects the string of tools to the cable.

6. *Rotary Drilling method*

There are two main types of rotary drilling methods:

Direct rotary methods, and

Reverse rotary method

In either case, a rotating bit is used as a drilling bit. The major difference is in the direction of the flowing fluid (Figure 13).

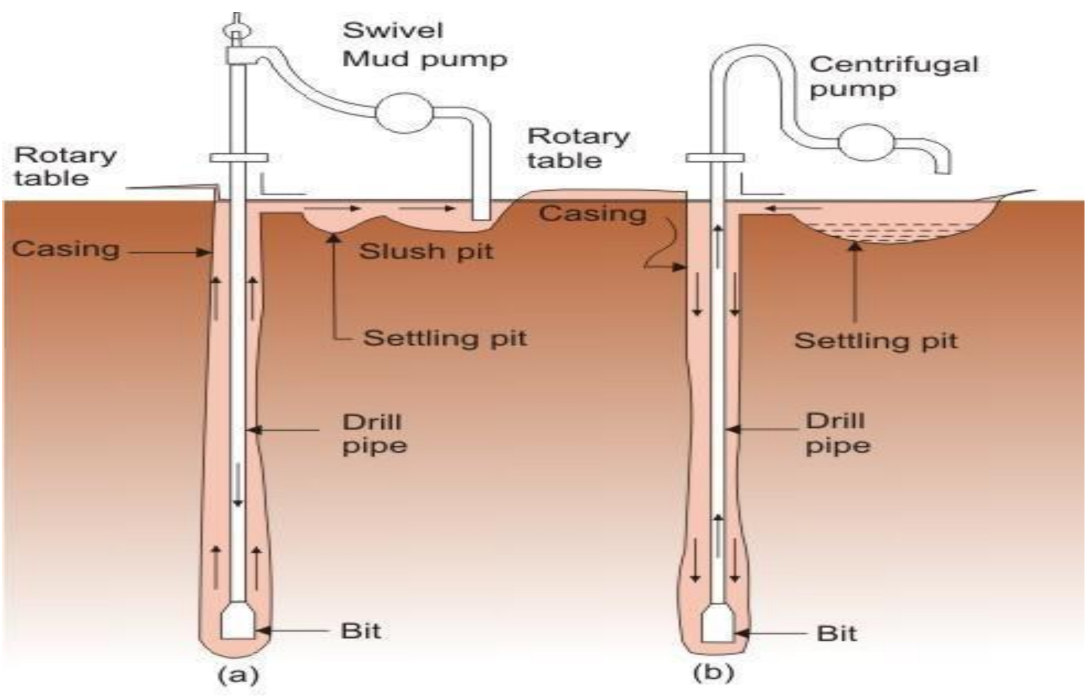


FIGURE . 13 ROTARY DRILLING (a) Hydraulic rotary (b) Reverse rotary

The rotary drilling method, also sometimes called the hydraulic rotary method of drilling, uses continuously circulating pumped fluid. The power to the drill bit is delivered to the bit by a rotating hallow steel pipe or drill pipe. The drilling fluid or bentonite slurry is pumped down through the drill pipe and out through a nozzle in the drill bit. The mud then rises to the surface through the hole and also removes the drilled formation material or muck. At the surface the fluid is led to a setting pit and then to a storage pit from where it is pumped back into the hole. Water and clay are added to the storage in to maintain quantity and consistency.

Well screens

For installation of well screens, different methods are used depending upon the design of the well, the type of well, locally available facility and the type of problems encountered in drilling operation. The Pull-back method is generally used with the cable-tool percussion method of well drilling. After the casing pipe has reached to the depth where the bottom of the screen is to be located, the sand that might have flowed into the pipe is removed. The well assembly consisting of screen and blind pipe lengths is lowered into the well. A heavy plate bail handle is provided at the bottom of the screen. The lowering of the assembly may be accomplished by suspending it by the bail handle using a flat hook attached to the sand line to engage the bail. After lowering the complete well screen assembly inside the casing pipe, the casing rip is pulled back.

For rotary drilled wells generally the Open-Hole method of screen installation used, though the Pull–Back method can also be used in this case too. In the open-hole method, after drilling the hole below the well caring, the drill stem is withdrawn and a telescope–size screen is lowered into the hole by any suitable method. The depth of the hole should be checked such that when the screen rests on the bottom of the hole, the lead packer should remain inside the lower end of the casing.

Gravel packing

Well can either manually ground packed or artificially ground packed. Natural ground packed condition is created by removing the fine sand from the formation either by pumping or by surging. An artificially gravel packed well has a envelop of specially grand sand or gravel placed around the well screen. Ground pack is designed on the basis of sieve analysis of the aquifer materials obtained during drilling. Aquifer consisting of coarse materials of less uniform sizes may not require any gravel pack.

Well Development

This process is used to remove sand, silt and other fine materials from a zone immediately surrounding the well screen. This is done by flow reversal through the screen openings so as to rearrange the formation particles in a naturally developed well and form a graded filter with materials of increasing porosity and permeability towards the well in an artificially gravel packed well, so that ultimately the well will yield clear sand free water.

UNIT IV

NECESSITY AND IMPORTANCE OF IRRIGATION

Introduction:

Both soil and water are essential for plant growth. The soil provides a structural base to the plants and allows the root system (the foundation of the plant) to spread and get a strong hold. The pores of the soil within the ***root zone*** hold moisture which clings to the soil particles by surface tension in the driest state or may fill up the pores partially or fully saturating with it useful nutrients dissolved in water, essential for the growth of the plants. The roots of most plants also require oxygen for respiration. Hence, full saturation of the soil pores leads to restricted root growth for these plants. (There are exceptions, though, like the rice plant, in which the supply of oxygen to the roots is made from the leaves through aerenchyma cells which are continuous from the leaves to the roots).

Since irrigation practice is essentially, an adequate and timely supply of water to the plant root zone for optimum crop yield, the study of the inter relationship between soil pores, its water-holding capacity and plant water absorption rate is fundamentally important. Though a study in detail would mostly be of importance to an agricultural scientist, in this lesson we discuss the essentials which are important to a water resources engineer contemplating the development of a command area through scientifically designed irrigation system.

Soil-water system

Soil is a heterogeneous mass consisting of a three phase system of solid, liquid and gas. Mineral matter, consisting of sand, silt and clay and organic matter form the largest fraction of soil and serves as a framework (matrix) with numerous pores of various proportions. The void space within the solid particles is called the soil pore space.

Decayed organic matter derived from the plant and animal remains are dispersed within the pore space. The soil air is totally expelled from soil when water is present in excess amount than can be stored.

On the other extreme, when the total soil is dry as in a hot region without any supply of water either naturally by rain or artificially by irrigation, the water molecules surround the soil particles as a thin film. In such a case, pressure lower than atmospheric thus results due to surface tension capillarity and it is not possible to drain out the water by gravity.

The salts present in soil water further add to these forces by way of osmotic pressure. The roots of the plants in such a soil state need to exert at least an equal amount of force for extracting water from the soil mass for their growth.

In the following sections, we discuss certain important terms and concepts related to the soil-water relations. First, we start with a discussion on soil properties and types of soils.

Soil properties

Soil is a complex mass of mineral and organic particles. The important properties that classify soil according to its relevance to making crop production (which in turn affects the decision making process of irrigation engineering) are:

- Soil texture
- Soil structure

Soil texture:

This refers to the relative sizes of soil particles in a given soil. According to their sizes, soil particles are grouped into gravel, sand, silt and day. The relative proportions of sand, silt and clay is a soil mass determines the soil texture. Figure 1 presents the textural classification of 12 main classes as identified by the US department of agriculture, which is also followed by the soil survey organizations of India.

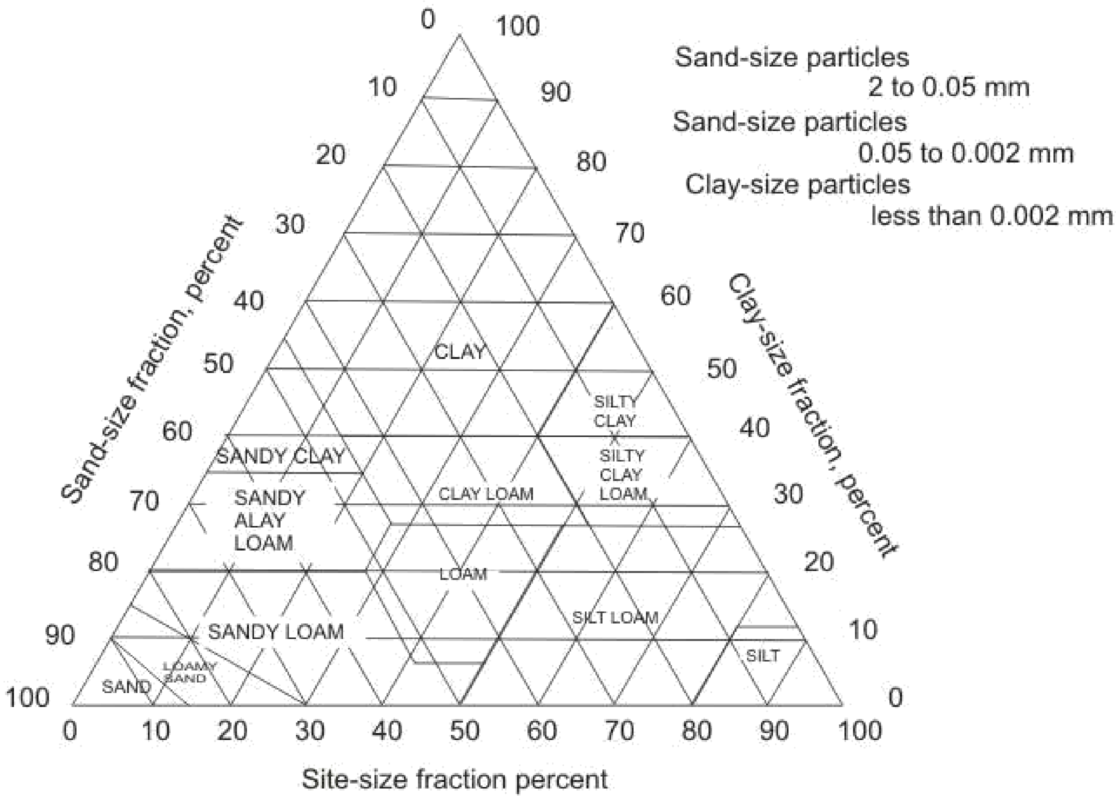


FIGURE 1. USDA textural classification chart

According to textural gradations a soil may be broadly classified as:

- Open or light textural soils: these are mainly coarse or sandy with low content of silt and clay.
- Medium textured soils: these contain sand, silt and clay in sizeable proportions, like loamy soil.
- Tight or heavy textured soils: these contain high proportion of clay.

Soil structure:

This refers to the arrangement of soil particles and aggregates with respect to each other. Aggregates are groups of individual soil particles adhering together. Soil structure is recognized as one of the most important properties of soil mass, since it influences aeration, permeability, water holding capacity, etc. The classification of soil structure is done according to three indicators as:-

Type: there are four types of primary structures-platy, prism-like, block like and spheroidal.

Class: there are five recognized classes in each of the primary types. These are very fine, fine, medium, coarse and very coarse.

Grade: this represents the degree of aggradation that is the proportion between aggregate and unaggregated material that results when the aggregates are displaced or gently crushed. Grades are termed as structure less, weak, moderate, strong and very strong depending on the stability of the aggregates when disturbed.

Soil classification

Soils vary widely in their characteristics and properties. In order to establish the interrelation ship between their characteristics, they need to be classified. In India, the soils may be grouped into the following types:

Alluvial soils: These soils are formed by successive deposition of silt transported by rivers during floods, in the flood plains and along the coastal belts.

This group is by for the largest and most important soil group of India contributing the greatest share to its agricultural wealth. Though a great deal of variation exists in the type of alluvial soil available throughout India, the main features of the soils are derived from the deposition laid by the numerous tributaries of the Indus, the Ganges and the Brahmaputra river systems. These streams, draining the Himalayas, bring with them the products of weathering rocks constituting the mountains, in various degrees of fineness and deposit them as they traverse the plains. Alluvial soils textures vary from clayey loam to sandy loam. The water holding capacity of these soils is fairly good and is good for irrigation.

Black soils: This type of soil has evolved from the weathering of rocks such as basalts, traps, granites and gneisses. Black soils are derived from the Deccan trap and are found in Maharashtra, western parts of Madhya Pradesh, parts of

Andhra Pradesh, parts of Gujarat and some parts of Tamilnadu. These soils are heavy textured with the clay content varying from 40 to 60 percent.the soils possess high water holding capacity but are poor in drainage.

Red soils: These soils are formed by the weathering of igneous and metamorphic rock comprising gneisses and schist's. They comprise of vast areas of Tamil nadu, Karnataka, Goa, Daman & Diu, south-eastern Maharashtra, Eastern Andhra Pradesh, Orissa and Jharkhand. They also are in the Birbhum district of West Bengal and Mirzapur, Jhansi and Hamirpur districts of Uttar pradesh. The red soils have low water holding capacity and hence well drained.

Laterites and Lateritic soils: Laterite is a formation peculiar to India and some other tropical countries, with an intermittently moist climate. Laterite soils are derived from the weathering of the laterite rocks and are well developed on the summits of the hills of the Karnataka, Kerala, Madhya Pradesh, The eastern ghats of Orissa, Maharashtra, West Bengal, Tamilnadu and Assam. These soils have low clay content and hence possess good drainage characteristics.

Desert soils: A large part of the arid region, belonging to western Rajasthan, Haryana, Punjab, lying between the Indus river and the Aravalli range is affected by the desert conditions of the geologically recent origin. This part is covered by a mantle of blown sand which, combined with the arid climate, results in poor soil development. They are light textured sandy soils and react well to the application of irrigation water.

Problem soils: The problem soils are those, which owing to land or soil characteristics cannot be used for the cultivation of crops without adopting proper reclamation measures. Highly eroded soils, ravine lands, soils on steeply sloping lands etc. constitute one set of problem soils. Acid, saline and alkaline soils constitute another set of problem soil.

Some of the major soil groups of the country are listed in the following table:

Zone	Name	Climate	Regions	Major soil group
1	Western Himalayan Region	Humid	Jammu & Kashmir, Himachal pradesh, Uttaranchal	Submontane soils, Hill and terai soils
2	Bengal-Assam Basin	Humid	West Bengal, Assam	Riverine alluvium, terai soils, lateritic soils, red-yellow loams
3	Eastern Himalayan Region and bay islands	Humid	Andaman & Nicobar Islands, Arunachal Pradesh, Nagaland, Manipur, Tripura, Meghalaya	Red loamy soils, lateritic soils, red yellow soils, alluvial soils
4	Sutlej-Ganga Plains	Sub-Humid	Pradesh, Bihar, Delhi, Uttaranchal	alluvium alkaline soils, red yellow loams, mixd red and black soil s
5	Eastern and south eastern uplands	Sub-Humid to Humid	Orissa, Jharkhand, Chattisgarh, Andhra Pradesh	Lateritic soils, red yellow loams, mixed red and black soils, red loamy soils, coastal alluvium alluvial soils, red yellow soils, medium to deep black soil s

6	Western plains	Arid	Harayana, Rajasthan, Dadra & Nagar Haveli	Lateritic soils, red yellow loams, mixed red and black soils, red loamy soils, coastal alluvium alluvial soils, red yellow soils, medium to deep black soil s
7	Lava plateau and central highlands	Semi arid	Maharashtra, Goa, Madhya Pradesh, Daman & Diu	Riverine alluvium, coastal alluvium, mixed red and black soils, skeletal soils, shallow deep black soils and red sandy soil s
8	Western Karnataka Plateau	Humid to semi arid	Karnataka, tamil Nadu, Pondicherry, Lakshadweep islands	Lateritic soils, red sandy Coastal alluvium and red loamy soils.

Classification of soil water

As stated earlier, water may occur in the soil pores in varying proportions. Some of the definitions related to the water held in the soil pores are as follows:

- **Gravitational water:** A soil sample saturated with water and left to drain the excess out by gravity holds on to a certain amount of water. The volume of water that could easily drain off is termed as the gravitational water. This water is not available for plants use as it drains off rapidly from the root zone.

- **Capillary water:** the water content retained in the soil after the gravitational water has drained off from the soil is known as the capillary water. This water is held in the soil by surface tension. Plant roots gradually absorb the capillary water and thus constitute the principle source of water for plant growth.

- **Hygroscopic water:** the water that an oven dry sample of soil absorbs when exposed to moist air is termed as hygroscopic water. It is held as a very thin film over the surface of the soil particles and is under tremendous negative (gauge) pressure. This water is not available to plants.

The above definitions of the soil water are based on physical factors. Some properties of soil water are not directly related to the above significance to plant growth. These are discussed next.

Soil water constants

For a particular soil, certain soil water proportions are defined which dictate whether the water is available or not for plant growth. These are called the soil water constants, which are described below.

Saturation capacity: this is the total water content of the soil when all the pores of the soil are filled with water. It is also termed as the maximum water holding capacity of the soil. At saturation capacity, the ***soil moisture tension*** is almost equal to zero.

Field capacity: this is the water retained by an initially saturated soil against the force of gravity. Hence, as the gravitational water gets drained off from the soil, it is said to reach the field capacity. At field capacity, the macro-pores of the soil

are drained off, but water is retained in the micropores. Though the soil moisture tension at field capacity varies from soil to soil, it is normally between 1/10 (for clayey soils) to 1/3 (for sandy soils) atmospheres.

Permanent wilting point: plant roots are able to extract water from a soil matrix, which is saturated up to field capacity. However, as the water extraction proceeds, the moisture content diminishes and the negative (gauge) pressure increases. At one point, the plant cannot extract any further water and thus ***wilts.***

Two stages of wilting points are recognized and they are:

Temporary wilting point: this denotes the soil water content at which the plant wilts at day time, but recovers during right or when water is added to the soil.

Ultimate wilting point: at such a soil water content, the plant wilts and fails to regain life even after addition of water to soil.

It must be noted that the above water contents are expressed as percentage of water held in the soil pores, compared to a fully saturated soil. Figure 2 explains graphically, the various soil constants; the full pie represents the volume of voids in soil.

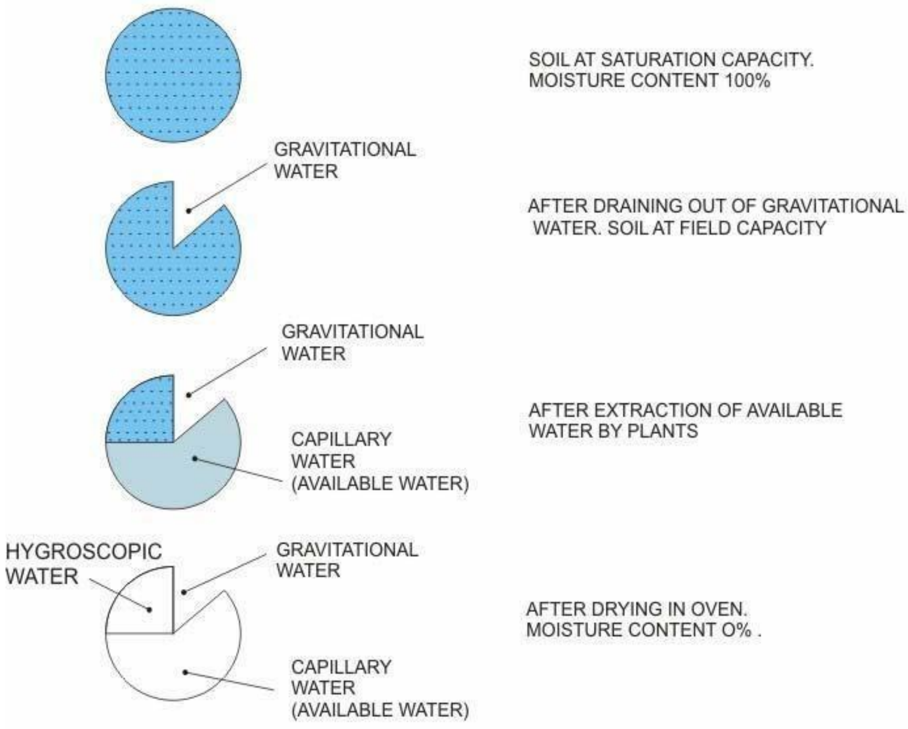


FIGURE 2 . Classification of soil water

As shown in Figure 2, the available water for plants is defined as the difference in moisture content of the soil between field capacity and permanent wilting point.

Field capacity and Permanent wilting point: Although the pie diagrams in Figure 2 demonstrate the drying up of saturated soil pores, all the soil constants are expressed as a percentage by weight of the moisture available at that point compared to the weight of the dried soil sand sample.

Soil water constants expressed in depth units:

In the last section, the soil water constants were mentioned as being expressed as weight percentages of the moisture content (that is amount of water) held by the water at a certain state with respect to the weight of the dried soil sample. The same may also be expressed as volume of water stored in the root zone of a field per unit area. This would consequently express the soil water constants as units of depths. The conversion from one form to the other is presented below:

Assume the following:

- Root zone depth = D (m)
- Specific weight of soil = γ_S (kg/m^3)
- Specific weight of water = γ_W (kg/m^3)
- Area of plot considered = 1m x 1m

Hence, the weight of soil per unit area would be: γ_S x 1 x D (kg)

The weight of water held by the soil per unit area would be equal to: γ x 1 x d

Where d is equivalent depth of water that is actually distributed within the soil pores. Hence the following constants may be expressed as:

$$\text{Field capacity} = \frac{\text{Weight of water held by soil per unit area}}{\text{Weight of soil per unit area}}$$

$$= \frac{\gamma w * 1 * d}{\gamma s * 1 * D} \qquad (1)$$

Thus, depth of water (***d Fc***) held by soil at field capacity (***FC***)

$$= \frac{\gamma_s}{\gamma_w} * D * FC \qquad (2)$$

Similarly, depth of water (***d wp***) held by soil at permanent wilting point (***PWP***)

$$= \frac{\gamma_s}{\gamma_w} * D * PWP \qquad (3)$$

Hence, depth of water (***d Aw***) available to plants

$$= \frac{\gamma_s}{\gamma_w} * D * [FC - PWP] \qquad (4)$$

Therefore, the depth of water available to plants per meter depth of soil

$$= \frac{\gamma_s}{\gamma_w} [FC - PWP] \qquad (5)$$

It may be noted that plants cannot extract the full available water with the same efficiency. About 75 percent of the amount is rather easily extracted, and it is called the readily available water. The available water holding capacity for a few typical soil types are given as in the following table:

Soil Texture	Field Capacity (FC) percent	Permanent Wilting Point (PWP) percent	Bulk Density(**γs**) Kg/m^3	Available water per meter depth of soil profile(m)
Sandy	5 to 10	2 to 6	1500 to 1800	0.05 to 0.1
Sandy loam	10 to 18	4 to 10	1400 to 1600	0.09 to 0.16
Loam	18 to 25	8 to 14	1300 to 1500	0.14 to 0.22
Clay loam	24 to 32	11 to 16	1300 to 1400	0.17 to 0.29
Clay	32 to 40	15 to 22	1200 to 1400	0.20 to 0.21

Water absorption by plants

Water is absorbed mostly through the roots of plants, though an insignificant absorption is also done through the leaves. Plants normally have a higher concentration of roots close to the soil surface and the density decreases with depth as shown in Figure 3.

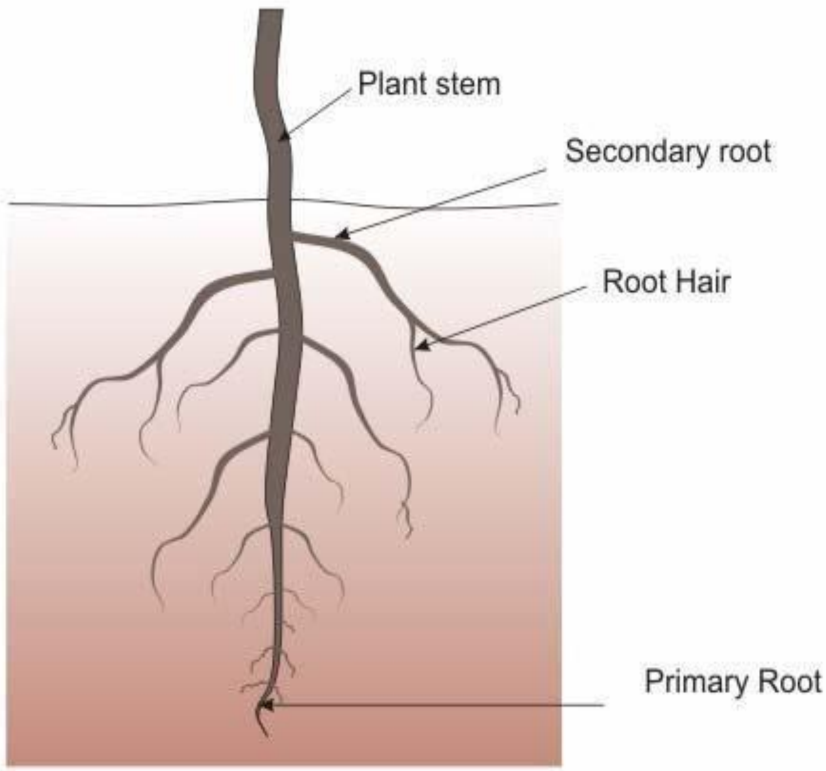


FIGURE 3. Typical root density variation of a plant with depth.

In a normal soil with good aeration, a greater portion of the roots of most plants remain within 0.45m to 0.60m of surface soil layers and most of the water needs of plants are met from this zone. As the available water from this zone decreases, plants extract more water from lower depths. When the water content of the upper soil layers reach wilting point, all the water needs of plants are met from lower layers. Since there exists few roots in lower layers, the water extract from lower layers may not be adequate to prevent wilting, although sufficient water may be available there.

When the top layers of the root zone are kept moist by frequent application of water through irrigation, plants extract most of the water (about 40 percent) from the upper quarter of their root zone. In the lower quarter of root zone the water extracted by the plant meets about 30 percent of its water needs. Further below, the third quarter of the root zone extracts about 20 percent and the lowermost quarter of root zone extracts the remaining about 10 percent of the plants water. It may be noted that the water extracted from the soil by the roots of a plant moves upwards and essentially is lost to the atmosphere as water vapours mainly through the leaves. This process, called transpiration, results in losing almost 95percent of water sucked up. Only about 5percent of water pumped up by the root system is used by the plant for metabolic purpose and increasing the plant body weight.

Watering interval for crops

A plot of land growing a crop has to be applied with water from time to time for its healthy growth. The water may come naturally from rainfall or may supplemented by artificially applying water through irrigation. A crop should be irrigated before it receives a set back in its growth and development. Hence the interval between two irrigations depends primarily on the rate of soil moisture depletion. Normally, a crop has to be irrigated before soil moisture is depleted below a certain portion of its availability in the root zone depending on the type pf plant. The intervals are shorter during summer than in winter. Similarly, the intervals are shorter for sandy soils than heavy soils. When the water supply is very limited, then the interval may be prolonged which means that the soil moisture is allowed to deplete below 50percent of available moisture before the next irrigation is applied. The optimum rates of soil moisture for a few typical crops are given below (Reference: Majumdar, D K, 2000)

- Maize : Field capacity to 60 percent of availability
- Wheat : Field capacity to 50 percent of availability
- Sugarcane: Field capacity to 50 percent of availability
- Barley : Field capacity to 40 percent of availability
- Cotton : Field capacity to 20 percent of availability

As for rice, the water requirement is slightly different than the rest. This is because it requires a constant standing depth of water of about 5cm throughout its growing period. This means that there is a constant percolation of water during this time and it has estimated that about 50 to 70 percent of water applied to the crop is lost in this way.

For most of the crops, except rice, the amount of water applied after each interval should be such that the moisture content of the soil is raised to its field capacity. The soil moisture depletes gradually due to the water lost through evaporation from the soil surface and due to the absorption of water from the plant roots, called transpiration more of which has been discussed in the next session. The combined effect of evaporation and transpiration, called evapo-transpiration (ET) decides the soil water depletion rate for a known value of ET (which depends on various factors, mainly climate); it is possible to find out the irrigation interval.

Some of the operational soil moisture ranges of some common crops are given below:

Rice:

This crop is grown both in lowland and upland conditions and throughout the year in some parts of the country. For lowland rice, the practice of keeping the soil saturated or upto shallow submergence of about 50mm throughout the growing period has been found to be the most beneficial practice for obtaining maximum yields. When water resources are limited, the land must be submerged atleast during critical stages of growth. The major portion of the water applied to the rice crop, about 50-75% is lost through deep percolation which varies with the texture of the soil. Since the soil is kept constantly submerged for rice growth, all the pores are completely filled with water through it is in a state of continuous downward movement. The total water required by the rice plant is about 1.0 to 1.5m for heavy soils and soils with high water table; 1.5 to

2.0m for medium soils and 2.0 to 2.5 for light soils with deep water table.

Wheat:

The optimum soil moisture range for tall wheats is from the field capacity to 50% of availability. The dwarf wheats need more wetness, and the optimum moisture range is from 100 to 60 percent availability. The active root zone of the crops varies from 0.5 to

0.75m depending upon the soil type. The total water requirement for wheat plants vary from 0.25m to 0.4 m in northern India to about 0.5m to 0.6m in Central India.

Barley:

This crop is similar to wheat in its growing habits, but can withstand more droughts because of the deeper and well spread root system. The active root zone of Barley extends between 0.6m to 0.75m on different soil types. The optimum soil moisture ranges from the field capacity to 40% of availability.

Maize:

The crop is grown almost all over the country. The optimum soil moisture range is from 100 to 60% of availability in the maximum root zone depth which extends from 0.4 to 0.6 on different soil types. The actual irrigation requirement of the crop varies with the amount of rainfall. In north India, 0.1m and 0.15m is required to establish the crop before the onset of monsoon. In the south, it is found that normal rain fall is sufficient to grow the crop in the monsoon season where as 0.3m of water is required during water.

Cotton:

The optimum range of soil moisture for cotton crop is from the field capacity to 20% of available water. He root zone varies upto about 0.75m. The total water requirement is about 0.4m to 0.5m.

Sugarcane:

The optimum soil moisture for sugarcane is about 100 to 50 percent of water availability in the maximum root zone, which extends to about 0.5m to 0.75m in depth. The total water depth requirement for sugarcane varies from about 1.4m to 1.5m in Bihar; 2.2m –2.4 m in Karnataka; and 2.0 – 2.3m in Madhya Pradesh.

Importance of water in plant growth

During the life cycle of a plant water, among other essential elements like air and fertilizers, plays a vital role, some of the important ones being:

- Water maintains the turgidity of the plant cells, thus keeping the plant erect. Water accounts for the largest part of the body weight of an actively growing plant and it constitutes 85 to 90 percent of the body weight of young plants and 20 to 50 percent of older or mature plants.

- Water provides both oxygen and hydrogen required for carbohydrate synthesis during the photosynthesis process.

- Water acts as a solvent of plant nutrients and helps in the uptake of nutrients from soil.

- Food manufactured in the green parts of a plant gets distributed throughout the plant body as a solution in water.

- Transpiration is a vital process in plants and does so at a maximum rate (called the potential evapo transpiration rate) when water is available in adequate amount. If soil moisture is not sufficient, then the transpiration rate is curtailed, seriously affecting plant growth and yield.

- Leaves get heated up with solar radiation and plants help to dissipate the heat by transpiration, which itself uses plant water.

Irrigation water quality

In irrigation agriculture, the quality of water used for irrigation should receive adequate attention. Irrigation water, regardless of its source, always contains some soluble salts in it. Apart from the total concentration of the dissolved salts, the concentration of some of the individual salts, and especially those which are most harmful to crops, is important in determining the suitability of water for irrigation. The constituents usually determined by analyzing irrigation water are the electrical conductivity for the total dissolved salts, soluble sodium percentage, sodium absorption ratio, boron content, PH, cations such as calcium, magnesium, sodium, potassium and anions such as carbonates, bicarbonates, sulphates, chlorides and nitrates.

Water from rivers which flow over salt effected areas or in the deltaic regions has a greater concentration of salts sometimes as high as 7500 ppm or even more. The quality of tank or lake water depends mainly on the soil salinity in the water shed areas and the aridity of the region. The quality of ground water resources, that is, from shallow or deep wells, is generally poor under the situations of

- high aridity
- high water table and water logged conditions
- in the vicinity of sea water on the basis of suitability of water for irrigation, the water may be classified under three categories, which are shown in the following table:

Class	Electrical Conductivity (micro-ohm/cm)	Total Dissolved Solids (ppm)	Exchangeable sodium (percentage)	Chloride (ppm)	Sulphates (ppm)	Boron (ppm)	Remarks
I	0-1000	0-700	0-60	0-142	0-192	0-0.5	Excellent to Good for irrigation
II	1000-3000	700-2000	60-75	142-355	192-480	0.5-2.0	Good to injurious; Suitable only with permeable soils and moderate teaching. Harmful to more sensitive crops.
III	>3000	>2000	>75	>355	>480	>2.0	Unfit for irrigation

Important Definitions

1. Root Zone: The soil root zone is the area of the soil around the plant that comes in contact with the plant root (Figure 4).

2. Soil Moisture tension: In soils partially saturated with water there is moisture tension, which is equal in magnitude but opposite in sign to the soil water pressure. Moisture tension is equal to the pressure that must be applied to the soil water to bring it to a hydraulic equilibrium, through a porous permeable wall or membrane, with a pool of water of the same composition.

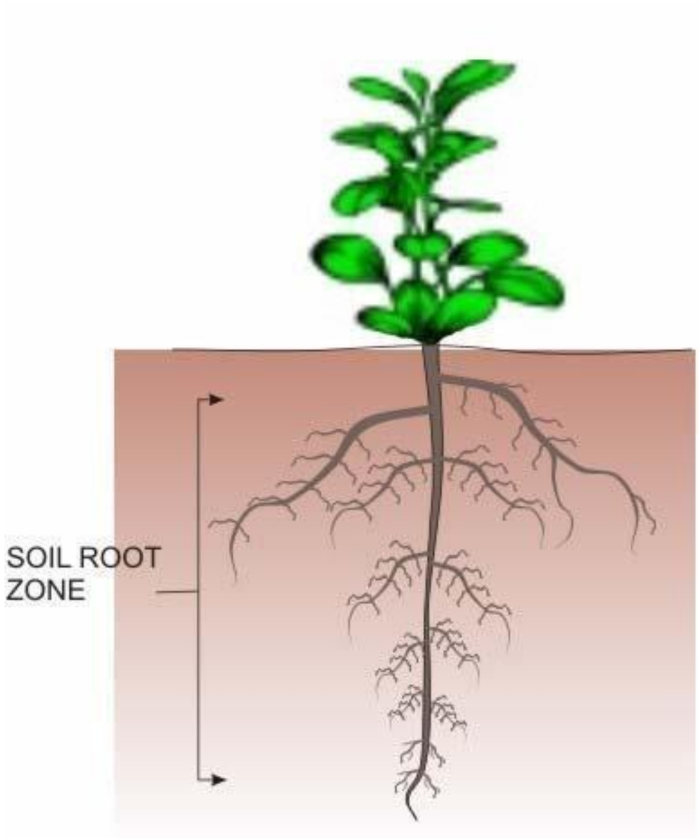


FIGURE 4 **Definition of soil root zone**

3. Wilts: Wilting is drooping of plants. Plants bend or hang downwards through tiredness or weakness due to lack of water.

Introduction

A plot of land growing a certain crop or a combination of crops has to be supplied with water from time to time. Primarily, the plot or field is expected to receive water from rain falling on the land surface. But, as we know, the distribution of rain is rather uncertain both in time and space. Also some of the rain as in a light shower does not reach the ground as it may be intercepted by the leaves of the plant during a heavy downpour; much of the water might flow away as surface runoff. Hence, only a certain amount of falling rain may be effective in raising the soil moisture that is actually useful for plant growth. Hence, for proper crop growth, the effective rain has to be supplemented by artificially applying water to the field by irrigation.

If the area of the field is small, water may be supplied from the local ground water source. If the field is large, supplemented irrigation water may be obtained from a local surface water source, like a river, if one is available nearby. The work of a water resources engineer therefore would be to design a suitable source for irrigation after knowing the demand of water from field data. In this lesson, we proceed on to find out the methods by which estimation may be made for irrigation water demand.

Crop water requirement

It is essential to know the water requirement of a crop which is the total quantity of water required from its sowing time up to harvest. Naturally different crops may have different water requirements at different places of the same country, depending upon the climate, type of soil, method of cultivation, effective rain etc.

The total water required for crop growth is not uniformly distributed over its entire life span which is also called crop period. Actually, the watering stops same time before harvest and the time duration from the first irrigation during sowing up to the last before harvest is called base period. Though crop period is slightly more than the base period, they do not differ from practical purposes.

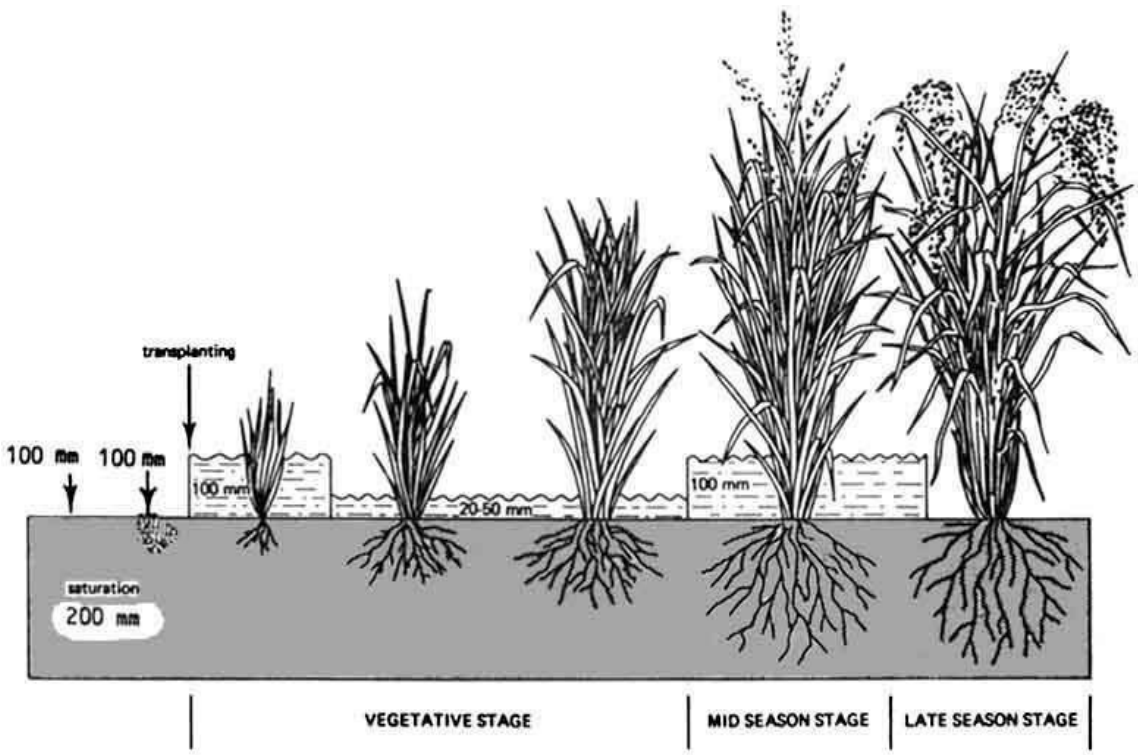


FIGURE 1. Variation in the requirement of water for paddy with stage of growth
(Image courtesy: Food and Agriculture Organisation, FAO)

Sometimes, in the initial stages before the crop is sown, the land is very dry. In such cases, the soil is moistened with water as t helps in sowing the crops. This is known as ***paleo*** irrigation. A term ***kor*** watering is used to describe the watering given to a crop when the plants are still young. It is usually the maximum single watering required, and other waterings are done at usual intervals.

The total depth of water required to raise a crop over a unit area of land is usually called ***delta***. Some typical values of delta for common crops in some regions of India are as follows:

Rice

1000mm to 1500mm for heavy soils or high water table
1500mm to 2000mm for medium soils
2000 to 2500 for light soils or deep water table
1600mm for upland conditions

Wheat

250mm to 400mm in northern India
500mm to 600mm in Central India
Barley: 450mm

Maize

10. 100mm during rainy season
11. 500mm during winter season
12. 900mm during summer season
13. Cotton: 400 – 500mm

Sugarcane

- 1400mm to 1500mm in Bihar
- 1600mm to 1700mm in Andhra Pradesh
- 1700mm to 1800mm in Punjab
- 2200mm to 2400mm in Madhya Pradesh
- 2800mm to 3000mm in Maharashtra

Duty of water

The term ***duty*** means the area of land that can be irrigated with unit volume of irrigation water. Quantitatively, duty is defined as the area of land expressed in hectares that can be irrigated with unit discharge, that is, 1 cumec flowing throughout the base period, expressed in days.

Imagine a field growing a single crop having a base period B days and a Delta Δ mm which is being supplied by a source located at the head (uppermost point) of the field, as shown in Figures 2 and 3.

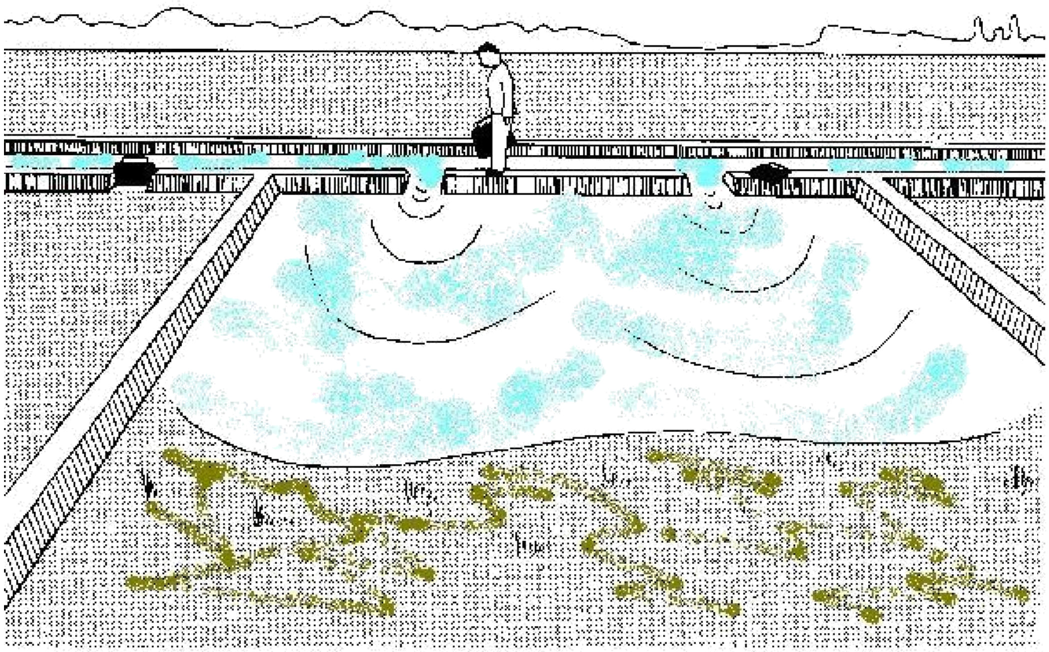


FIGURE 2. Border irrigation method of applying water at the head of a field
(Image courtesy: Food and Agriculture Organisation, FAO)

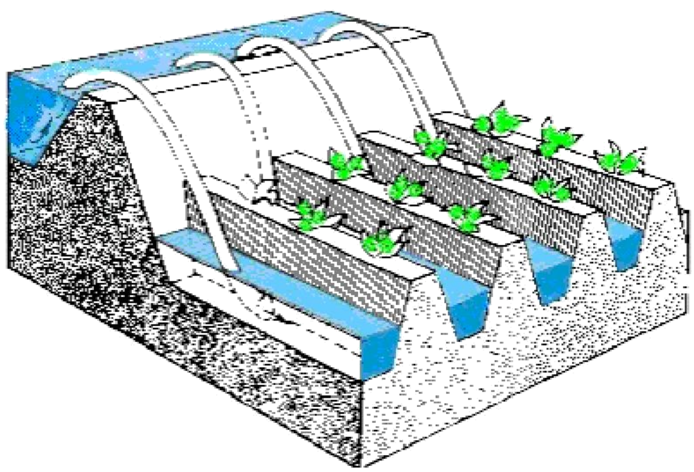


FIGURE 3. Furow irrigation method of applying water to a field

(Image courtesy: Food and Agriculture Organisation, FAO)

The water being supplied may be through the diversion of river water through a canal, or

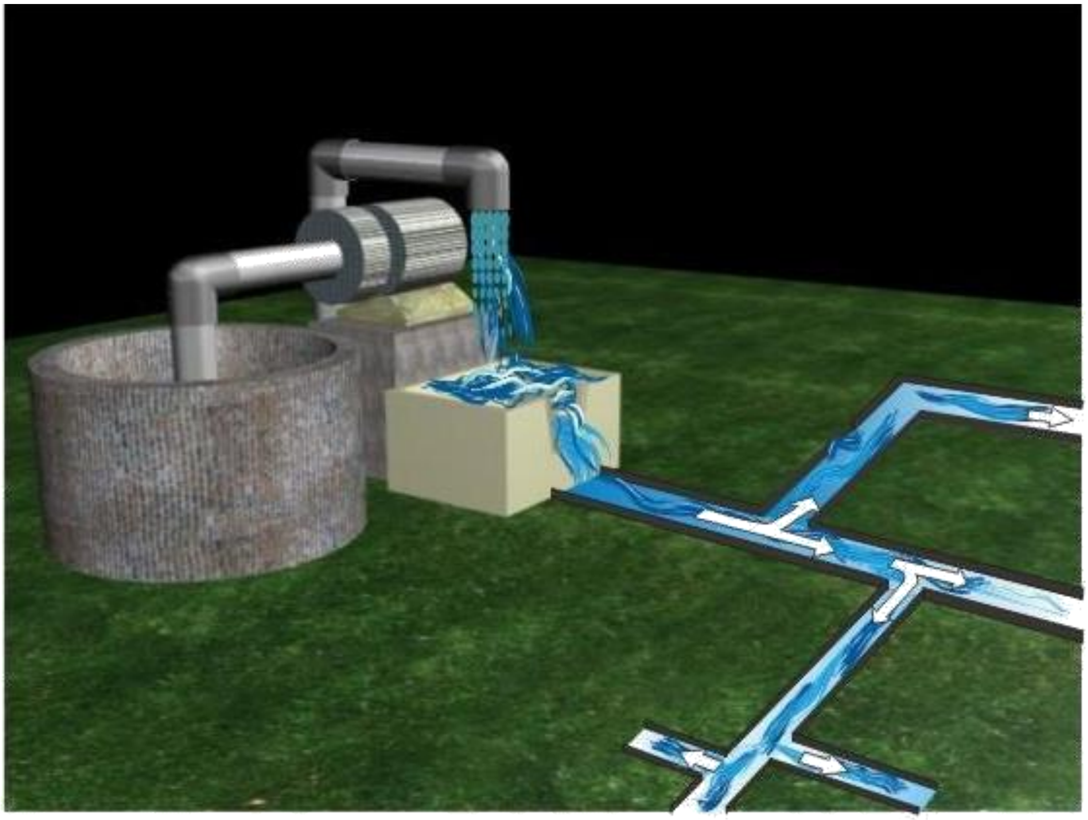


FIGURE 4. Water applied to field by pumping ground water

it could be using ground water by pumping (Figure 4).

the water supplied is just enough to raise the crop within D hectares of the field, then a relationship may be found out amongst all the variables as:

Volume of water supplied = $B*60*60*24\ m^3$

Area of crop irrigated = $D*10^4\ m^2$

Duty of irrigation water depends upon a number of factors; some of the important ones are as follows:

- **Type of crop:** As different crops require different amount of water for maturity, duties are also required. The duty would vary inversely as the water requirement of crop.
- **Climate season and type of soil:** Some water applied to the field is expected to be lost through evaporation and deep percolation. Evaporation loss has a direct bearing on the prevalent climate and percolation may be during drier seasons when the water table is low and soil is also dry. Percolation loss would be more for sandy soils than silty or clayey soils.

- **Efficiency of cultivation methods:** If the tillage and methods of water application are faulty and less efficient, then the amount of water actually reaching the plant roots would be less. Hence, for proper crop growth more water would be required than an equivalent efficient system. Also, if the water is conveyed over long distances through field channels before being finally applied to the field, then also the duty will rise due to the losses taking place in the channels.

Crop growing seasons in India

Each crop has its own sowing and harvesting seasons and it is important to have a knowledge of this which may help to decide the total water demand in a field having mixed crops.

In India, the northern and north eastern regions have two distinct cropping seasons. The first coinciding mostly with the South western monsoon is called ***kharif*** , which spans mostly from July to October. The other, called ***rabi***, spans generally over October to March. The summer season crops are planted sometime between April and June. In southern part of India, there is no such distinct season, but each region has its own classification of seasons.

Generally, the kharif is characterized by a gradual fall in temperature, more numerous cloudy days, low intensity, high relative humidity and cyclonic weather. During Rabi, there is a gradual rise in temperature, bright sunshine, near absence of cloud days, and a lower relative humidity.

The following table indicates some the regional cropping calendars in India.

State	Season	Local name	Growing month
Andhra Pradesh	Kharif	Serva or Abi	July – December
	Rabi	Dalwa or Tabi	December – April
	Summer	In limited areas	March/April – June
Assam	Pre-monsoon	Ahu	Mar/April–June/july
	-	Sali	June/July-Nov/Dec
	-	Boro	Nov - May
Bihar	Summer	-	March – July/Aug
	Autumn	-	May/June– Sept/Oct
	Winter	-	June – Nov/Dec
Gujarat	Kharif	Chomasu Dangar	June/July-Oct/Nov
	-	Unala Dangar	Dec – June
Haryana	Kharif	-	May/June– Sept/Oct
Himachal Pradesh	Kharif	-	June/July-Sept/Oct
Jammu & Kashmir	-	-	Jammu: June-Nov Kashmir: Last week of April - October
Karnataka	Kharif	-	June – Dec
	Summer	-	Jan-May/June
Kerala	first crop	Virippu	April-May/Sept-Oct
	Second crop	Mundakan	Sept-Oct/Dec-Jan
	Third crop	Punja	Dec/Jan-Mar/April
Madhya Pradesh	Kharif	-	June/July-Dec
Maharashtra	Kharif	-	June/July-Dec
Manipur	Kharif	-	Mar/June-Sept/Oct
Meghalaya	Kharif	-	May/June-Aug/Sept
	Rabi	-	----------------
Nagaland	Kharif	-	May/June-Nov/Dec
	Rabi	-	Feb - May
Orissa	-	Sarad	June-Dec
	-	Dalua	Dec-April
	-	Beali (short Duration)	April/May –Sept (Only in uplands)

Punjab	Kharif	-	May – Nov
Rajasthan	Kharif	-	June/July-Sept/oct
Tamil Nadu	-	Navarai	Jan-April
	-	Sornavari	April – July
	-	Kar or Kuruvai	June – August
	-	Samba	June/July-Nov/Dec
	-	Thaladi or Pishanam	Sept/Oct-Feb/March
Uttar Pradesh	Kharif	-	June – Oct
West Bengal	Pre-Kharif	Aus	April-Sept
	Kharif	Aman	June-Dec
	Summer	Boro	End Nov-Mid June

Variations in the country's irrigation demands

It may be appreciated that in India there is a large variation of rainfall, which is the primary source of irrigation in most parts of the country. In fact, the crops grown in various regions have been adapted according to the local rainfall availability. Water resources engineers are therefore concerned with arranging supplementary water to support the crops for seasonal variations of rainfall in order to ensure an assured crop harvest.

Further, due to variation in the type of soil over different regions of the country, the types of crop grown also varies- thus dictating the water requirement at different regions during different times. Hence, the country has been broadly classified into eight agro climatic zones, a list of which is given.

Cropping patterns

Planning of an irrigation project requires estimation of water demand of a cultivated area. Naturally, this would depend upon the type of crop grown. Since irrigation water may have to be supplied to one field growing a combination of crops or to many fields growing different crops, it is important to understand certain cropping practices which would be helpful in estimating the irrigation demand. Some of the prevalent practices are as follows:

8. Crops grown solely or mixed: Mixed cropping
9. Crops grown in a definite sequence: Rotational cropping
10. Land occupied by one crop during one season: Mono cropping
11. Land occupied by two crops: double cropping
12. Land sowed with more than one crop in a year: multiple cropping

Irrigation water need

For raising a field crop effectively, it is essential to supply water through artificial irrigation supplementing the rain falling over the plot of land and raising the soil moisture. Irrigation requirement for a typical crop and an assumed rainfall pattern may be illustrated as in Figure 5.

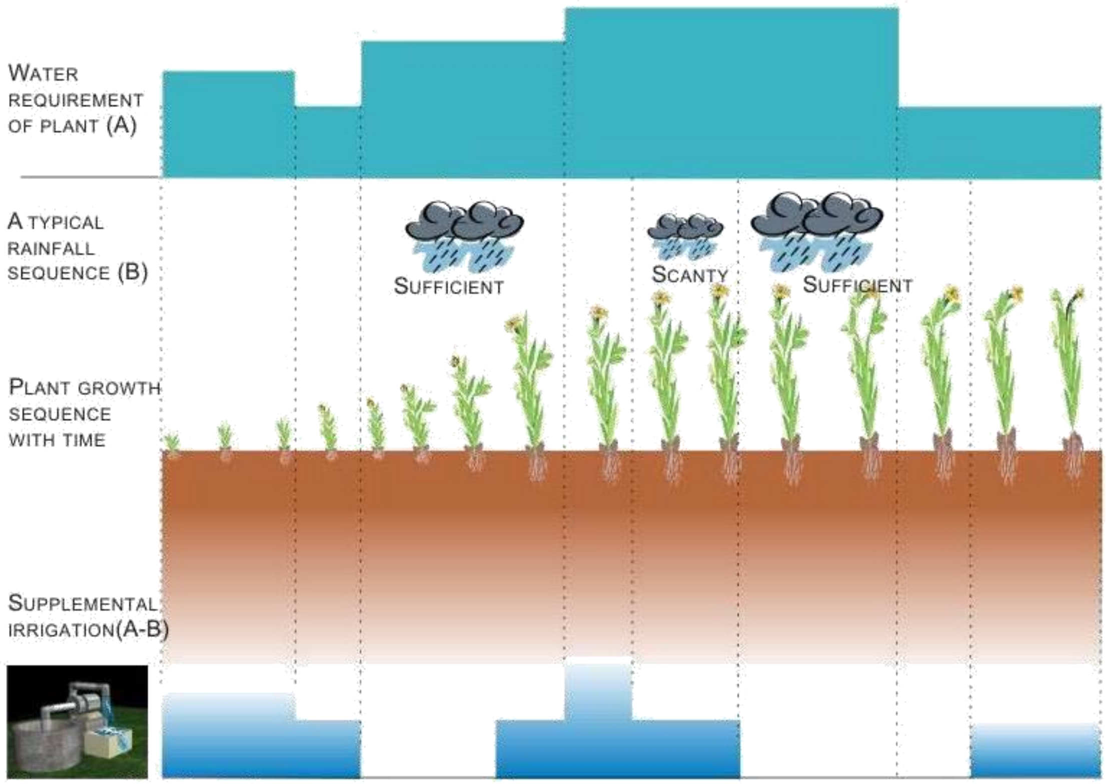


FIGURE 5 . Typical irrigation requirement of a crop and water provided naturally by rain or artificially by pumping

Hence, it may be seen that irrigation water requirement is rather a dynamic one. Also, the crop water requirement is shown with slight variation, it actually shows more variation, depending on the type of crop and the prevalent climate. Though farmers may be tempted to allow more water to the plants through supplemental irrigation, it must be remembered that there is an optimum water requirement schedule of each crop depending upon its stage of growth. It has been proved that at times application of more water may cause reduction in yield.

Variation of crop water requirement

The total water need for various plants, known as delta, has been discussed earlier. However, in planning the supply of irrigation water to a field crop, it is essential to estimate the water requirement of each plot of land growing a crop or crops at any point of time. This may be done by studying the dynamic interaction between a crop and the prevalent climate and the consequent water requirement.

The demand would, naturally be also dependant on the type of crop and its stage of growth.

Plant roots extract water from the soil. Most of this water doesn't remain in the plant, but escapes to the atmosphere as vapour through the plants leaves and stems, a process which is called ***transpiration*** and occurs mostly during daytime.

The water on the soil surface as well as the water attaching to the leaves and stem of a plant during a rainfall also is lost to the atmosphere by evaporation. Hence, the water need of a crop consists of transpiration plus evaporation, together called ***evapotranspiration***.

The effect of the major climatic factors on crop water needs may be summarized as follows:

- Sunshine
- Temperature
- Humidity
- Wind speed

The variation of evapotranspiration upon these factors is illustrated in Figure 6.

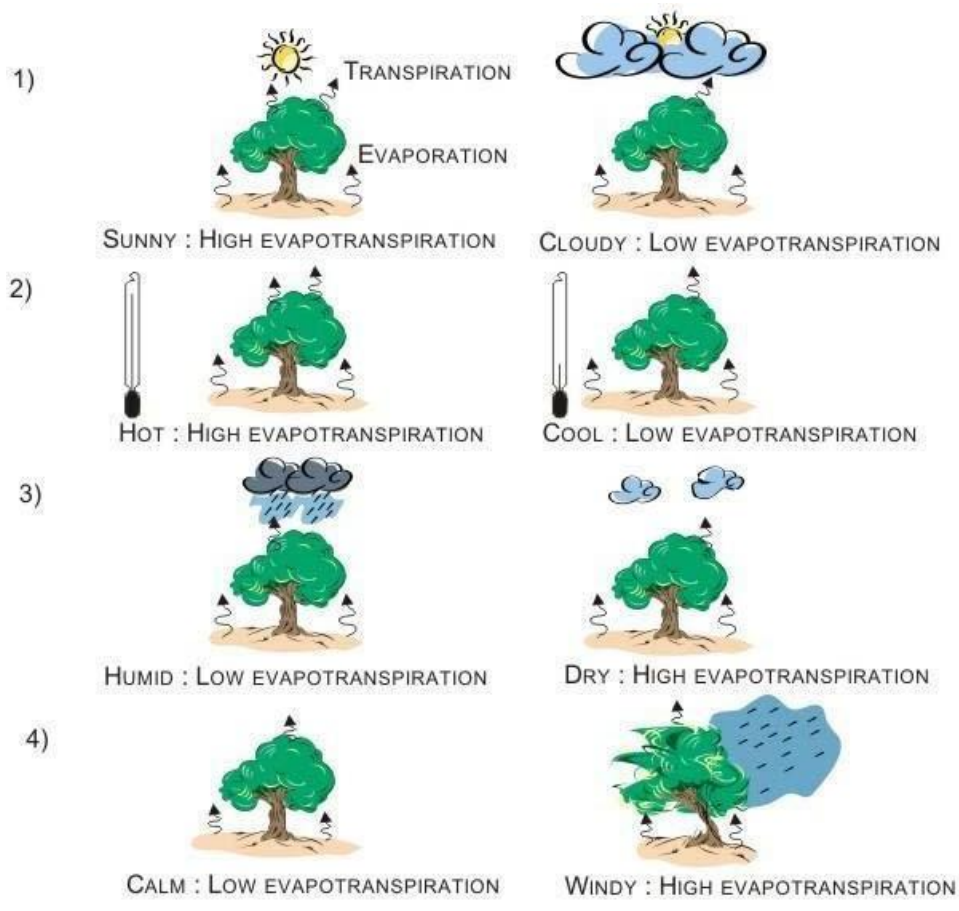


FIGURE 6. Dependence of evapotranspiration upon different climatological factors

Since the same crop grown in different climatic variations have different water needs, it has been accepted to evaluate the evapotranspiration rate for a standard or reference crop and find out that of all other crops in terms of this reference. Grass has been chosen as standard reference for this purpose. The evapotranspiration rate of this standard grass is, therefore, called the ***reference crop evapotranspiration*** and is denoted as ET_O, which is of course, the function of the climatic variables. Training Manual 3: Irrigation Water Needs published by the Food and Agricultural Organisation, (FAO) and available on-line through the under-mentioned web-site gives an idea about the variation of ET_O under different climatic conditions and is reproduced in the table below.

Table showing the daily variation of water needs of standard grass (in mm) under different climatic patterns (ET_O)

Climatic Zone	Mean daily Temperature		
	Low (<15^{o}C)	Medium (15^{o} - 25^{o}C)	High (>25^{o}C)
Desert/Arid	4-6	7-8	9-10
Semi-arid	4-5	6-7	8-9
Sub-humid	3-4	5-6	7-8
humid	1-2	3-4	5-6

Other methods have been devised to calculate ET_O for given values of climatic parameters. These are discussed in the next section. In this section, we proceed on to discuss, how to find crop water need, if ET_O is known.

Agricultural scientists have evaluated a factor called ***crop factor*** and denoted it by K_C, to evaluate specific crop water needs. Naturally, Kc would be different for different crops and would not be the same throughout the growth season of one type of crop. Thus, the crop evapotranspiration, denoted by ET_C is to be evaluated as under:

$$ET_O = K_C * ET_C \qquad (1)$$

Both ET_O and ET_C should be in the same units and generally, mm/day is used as a standard all over the world.

In order to simply the calculations, the factor K_C has been evaluated for 4 stages of a crop growth usually denoted as

1. Initial stage
2. Crop development stage
3. Mid-season stage
4. Late season stage

The FAO Training Manual 3 gives the growth stage periods and the corresponding KC values for some typical crops. In the table below, that for rice is presented.

Rice	Climate			
	Little wind		Strong wind	
Growth stage	Dry	Humid	Dry	Humid
0-60 days	1.1	1.1	1.1	1.1
Mid season	1.2	1.05	1.35	1.3
Last 30 days before harvest	1.0	1.0	1.0	1.0

It may be mentioned that any crop doesn't have a fixed total growth period, which is the summation of growth stage periods given above. There is usually a range, depending upon the variety of the crop and the condition in which it is cultivated.

The values of K C also depend upon the climate and particularly on humidity and wind

speed, as shown for rice in the above table. In general, the values of KC should be reduced by 0.05 if the relative humidity is high (>80%) and the wind speed is low (<2m/s). Likewise, the values should be increased by 0.05 if the relative humidity is low (<50%) and the wind speed is high (>5m/s).

For full details, the FAO training manual 3 may be consulted as KC values for other crops are evaluated in different manners. For some of the crops, the following table provides informatio

Crop	Variety	Crop growth stage				Total growth period
Cabbage/Carrot	Short duration	20 days	25 days	60 days	15 days	120 days
	Long duration	25 days	30 days	65 days	20 days	140 days
	KC	0.45	0.75	1.05	0.9	
Cotton/Fiax	Short duration	30 days	50 days	55 days	45 days	180
	Long duration	30 days	50 days	65 days	50 days	195
	Kc	0.45	0.75	1.15	0.75	
Lentil/Pulses	Short duration	20 days	30 days	60 days	40 days	150
	Long duration	25 days	35 days	70 days	40 days	170
	KC	0.45	0.75	1.1	0.5	
	Short	20	25	25	10	80

Maize	duration					
	Long duration	20	30	50	10	110
	KC	0.4	0.8	1.15	1.0	
Onion (dry)	Short duration	15	25	70	40	150
	Long duration	20	35	110	45	210
	KC	0.5	0.75	1.05	0.85	
Potato	Short duration	25	30	30	20	105
	Long duration	30	35	50	30	145
	KC	0.45	0.75	1.15	0.85	

Estimation of reference crop ET_O

Of the many methods available, the commonly used ones are two:

i. Experimental methods, using the experimentation data from evaporation pan.
ii. Theoretical methods using empirical formulae, that take into account, climatic parameters.

Experimental method

Estimation of ET_0 can be made using the formula

$$ET_O = Kpan \times Epan \qquad (2)$$

Where ET_O is the ***reference crop evapotranspiration*** in mm/day, Kpan is a coefficient called ***pan coefficient*** and Epan is the ***evaporation*** in mm/day from the pan.

The factor Kpan varies with the position of the equipment (say, whether placed in a fallow area or a cropped area), humidity and wind speed. Generally, the details are supplied by the manufacturers of the pan. For the ***US Class A evaporation pan***, which is also used in India, Kpan varies between 0.35 and 0.85, with an average value of 0.7.

It may be noticed that finding out ET_C would involve the following expression

$$ET_C = Kcrop \times ET_O = Kc \times Epan \times Kpan \qquad (3)$$

K_C has been discussed in the previous section. If instead, Kcrop x Kpan is taken as a single factor, say K, then ET_C may directly be found from Epan as under:

$ET_C = K \times E_{pan}$, where K may be called the crop factor (4)

The water management division of the Department of Agriculture, Government of India has published a list of factors for common crops and depending upon the stage of growth, which have to be multiplied with the evaporation values of the USWB Class A evaporation pan.

Theoretical methods

The important methods that have been proposed over the years take into account, various climatic parameters. Of these, only the following would be discussed, as they are the most commonly used.

Blanney-Criddle formula:

This formula gives an estimate of the mean monthly values of ET_O, which is stated as

$$ET_O = p\,(0.46\,T_{mean} + 8.13) \qquad (5)$$

Where p is the mean daily percentage of annual day time hours and has been estimated according to latitude; Tmean is the mean monthly temperature in degrees Centigrade and may be taken as ½ x (Tmax + Tmin) for a particular month. Thus using the Equation (1), one may evaluate ET_C for each month of the growing season, from which the total water need for the full growing season of the crop may be found out.

ET_o reference evapotranspiration [mm day^{-1}],

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}], G soil heat flux density [MJ m^{-2} day^{-1}],

T mean daily air temperature at 2 m height [°C], u_2 wind speed at 2 m height [m s^{-1}],

e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],

$e_s - e_a$ saturation vapour pressure deficit [kPa],
slope vapour pressure curve [kPa $°C^{-1}$],

g psychrometric constant [kPa $°C^{-1}$].

Application interval of irrigation water

The water need of a crop is usually expressed as mm/day, mm/month or mm/season, where season means the crop growing period. Whatever be the water need, it need not be applied each day. A larger amount of water may be applied once in a few days and it gets stored in the crop root zone, from where the plant keeps on extracting water.

Soon after irrigation, when the soil is saturated, up to the field capacity, the extraction of water from the soil by the plants is at the peak. This rate of water withdrawal decreases as the soil moisture depletes (Figure 7).

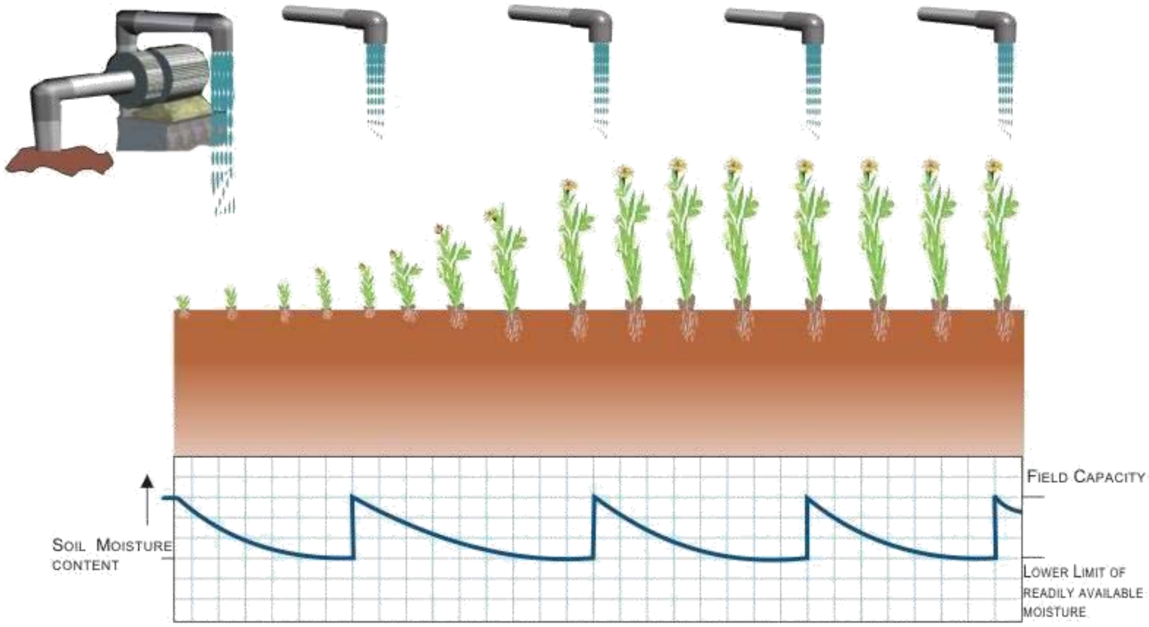


FIGURE 7. Rise and fall of soil moisture content due to irrigation and evapotranspiration

A stage is reached, in the moisture content of the soil, below which the plant is stressed to extract and unless the soil moisture is increased by application of water, the plant production would decrease. The difference of moisture content between field capacity (the maximum content of available water) and the lowest allowable moisture content is called the optimum soil water.

The optimum soil moisture range for some common crops is required from which the interval period of irrigation water may be estimated as follows:

$$\text{Irrigation period (days)} = \frac{\text{Net depth of soil depletion in the crop area just before irrigation (mm)}}{\text{ETc (mm/day)}}$$

Where the crop evapotranspiration rate (ETC) may be determined according to the crop type, growth stage and prevailing climate as mentioned in the previous sections.

The irrigation period, as calculated above, has not taken the soil retention characteristics. Naturally, a soil with greater water retentive capacity serves as a bigger water reservoir for crops and supply of irrigation can be delayed. Consequently, frequency of irrigation is lower and interval of irrigation is longer in heavier soils and in soils with good organic content and low content of soluble salts.

Further, the calculation of ETC as presented earlier and employed in the equation above to calculate irrigation period, what is called, the ***potential evapotranspiration*** (PET). This is the highest rate of water with drawl by an actively growing crop with abundant water supply. However as the soil moisture depletes, the ***actual evapotranspiration*** (AET) also decreases, as evident from the decrease in the gradient of the soil moisture curve with time in Figure 7. The

AET would also be different from the PET if the climatic conditions like humidity temperature etc vary from the ones assumed when calculating PET.

Nevertheless since PET is easier to estimate and since it would also be higher than AET, it is rational to consider PET, while designing the water requirement for a field of crop.

Total water requirement in growing a crop

The water that is required to irrigate a field or plot of land growing the particular crop not only has to satisfy the evapotranspiration needs for growing the crop, but would also include the following:

- Losses in the form of deep percolation while conveying water from the inlet of the field upto its last or tail end as the water gets distributed within the field
- Water requirement for special operations like land preparation, transplanting, leaching of salts, etc.

Further, the evapotranspiration requirement of crops (ET) really doesn't include the water required by crops for building up plant tissues, which is rather negligible compared to the evaporation needs. Hence ET_C is often equivalently taken as the ***consumptive irrigation requirement*** (CIR).

The ***net irrigation requirement*** (NIR) is defined as the amount of irrigation water required to be delivered in the field to meet the consumptive requirement of crop as well as other needs such as leaching, ***pre-sowing*** and ***nursery water requirement*** (if any). Thus,

$$NIR = CIR + LR + PSR + NWR \qquad (8)$$

Where

LR = Leaching requirement
PSR = Pre-sowing requirement

NWR = Nursery water requirement

Field Irrigation Requirement (FIR) is defined as the amount of water required to meet the net irrigation requirements plus the amount of water lost as surface runoff and through deep percolation. Considering a factor η_a called the water application efficiency or the field application efficiency which accounts for the loss of irrigation water during its application over the field, we have

$$FIR = \frac{NIR}{\eta_a} \qquad (9)$$

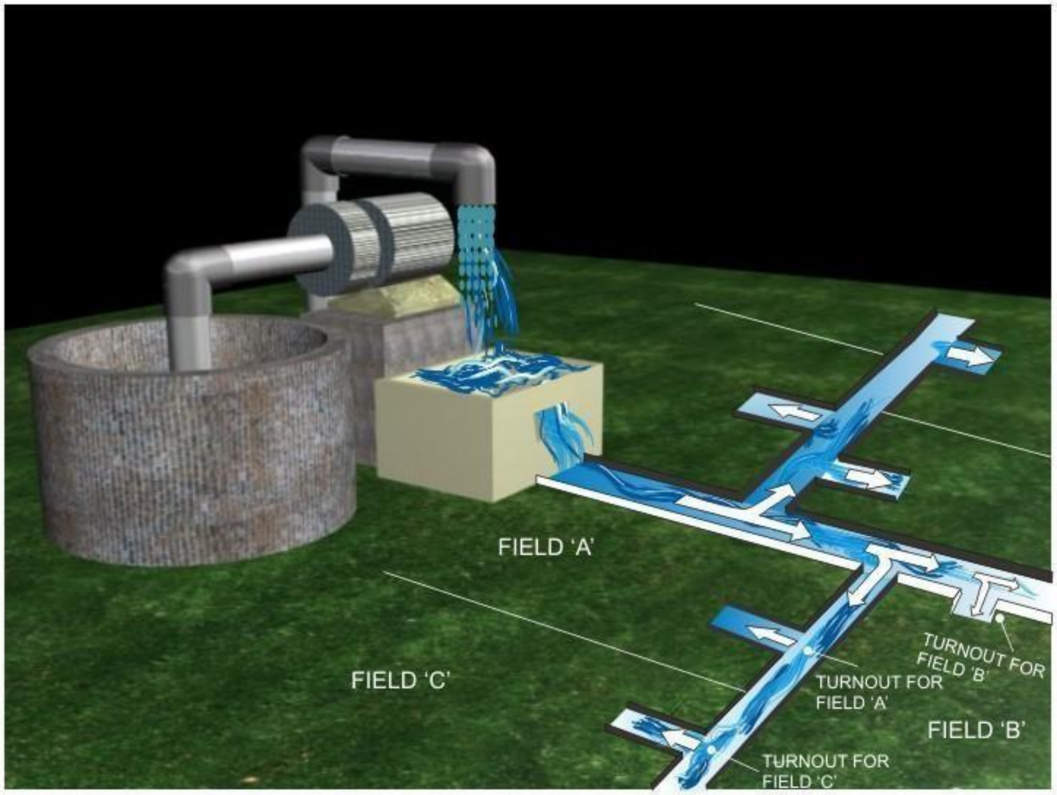


FIGURE 8. A typical ground water source irrigating a number of fields

Now, consider an irrigated area where there is a single source of water (say, a ground water pump) is supplying water to a number of fields and water is applied to each field by rotation (Figure 8). Naturally, some water is lost through the respective turnouts. Hence, the source must supply a larger amount of water than that required at any point of time by adding up the flows to the fields turnouts that are open at that point of time.

Thus, the capacity of the water supply source may be termed as the ***gross irrigation requirement*** (GIR), defined as:

$$GIR = \frac{FIR}{\eta_C} \qquad (10)$$

In the above equation, η_C is the ***water conveyance efficiency***.

Figure 9 shows the factors that decide the overall irrigation efficiency.

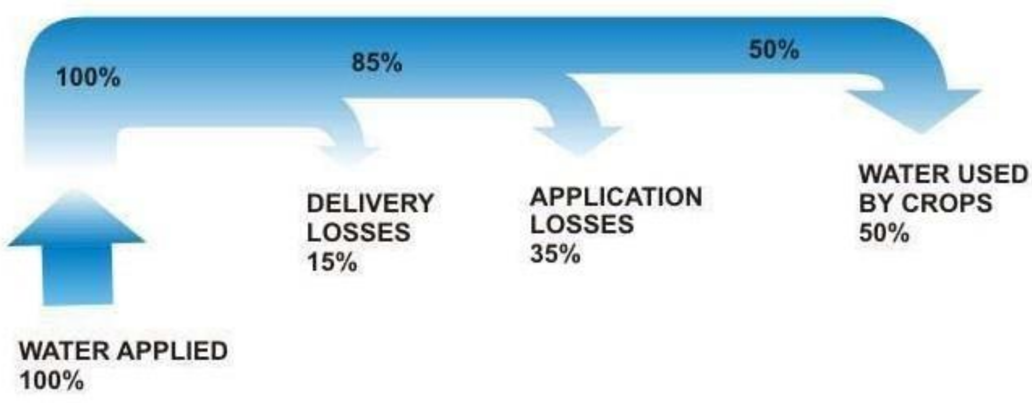


FIGURE 9. Typical values of losses in an irrigation system: factors affecting irrigation efficiency

Important terms related to crop water requirements and irrigation

Paleo irrigation

Sometimes, in the initial stages before the crop is sown, the land is very dry. This happens usually at the time of sowing Rabi crops because of hot September, when the soil may be too dry to be sown easily. In such a case, the soil is first moistured with water to help to sowing of seeds, and the water application for this purpose is known as Paleo Irrigation.

Kor watering

The total quality of water required by a crop is applied through a number of waterings at certain intervals throughout the base period of the crop. However, the quantity of water required to be applied during each of these waterings is not the same. In general, for all crops during the first watering after the plants have grown a few centimeters high, the quantity of water required is more than that during subsequent waterings. The first watering after the plants have grown a few centimeters high is known as Kor watering and the depth of water applied during watering is known as Kor depth. The watering must be done in a limited period which is known as the Kor period.

Outlet factor

The duty of water at the outlet that is at the turnout leading from the water courses and field channels on the field is known as the outlet factor.

Overlap allowance

It might happen that the crop of one season may sometimes overlap the next crop season for some period. During such a period of overlapping, irrigation water is required to be supplied simultaneously to the crops of both the seasons.

Thus there is extra demand of water during this period and thus the water supply must be increased by some amount. The extra discharge that has to be supplied for this purpose is known as Overlap allowance.

The Evaporation Pan

A shallow edged container used to hold water during observations for the determination of the quantity of evaporation at a given location. The U.S. Weather Bureau Class A pan is 4 feet in diameter, 10 inches deep, set up on a timber grillage so that the top rim is about 16 inches from the ground. The water level in the pan during the course of observation is maintained between 2 and 3 inches below the rim.

UNIT V
CLASSIFICATION OF CANALS

Many procedures have been developed over the years for the hydraulic design of open channel sections. The complexity of these procedures varies according to flow conditions as well as the level of assumption implied while developing the given equation. The Chezy equation is one of the procedures that was developed by a French engineer in 1768 (Henderson, 1966). The development of this equation was based on the dimensional analysis of the friction equation under the assumption that the condition of flow is uniform. A more practical procedure was presented in 1889 by the Irish engineer Robert Manning (Chow, 1959). The Manning equation has proved to be very reliable in practice.

Manning equation invokes the determination of flow velocity based on the slope of channel bed, surface roughness of the channel, cross-sectional area of flow, and wetted perimeter of flow. Using this equation, the solution procedures are direct for determination of flow velocity, slope of channel bed, and surface roughness. However, the solution for any unknown related to the cross-sectional area of flow and wetted perimeter involves the implementation of an implicit recursive solution procedure which cannot be achieved analytically. Many implicit solution procedures such as the Newton-Raphson, Regula-Falsi (false position), secant, and the Van Wijngaarden-Dekker-Brent Methods (Press et al., 1992).

One of the important topics in the area of Free surface flows is the design of channels capable of transporting water between two locations in a safe, cost - effective manner.

Even though economics, safety, and aesthetics must always be considered, in this unit thrust is given only to the hydraulic aspects of channel design. For that discussion is confined to the design of channels for uniform flow. The two types of channels considered are

1. lined or non-erodible;
2. unlined, earthen, or erodible.

There are some basic issues common to both the types and are presented in the following paragraphs.

1. Shape of the cross section of the canal.
2. Side slope of the canal.
3. Longitudinal bed slope.
4. Permissible velocities - Maximum and Minimum. Roughness coefficient.
5. Free board.

1. Shape of cross section

From the Manning and Chezy equation, it is obvious that the conveyance of a channel increases as the hydraulic radius increases or as the wetted perimeter decreases. Thus, there is among all channel cross sections of a specified geometric shape and ares an optimum set of dimensions for that shape from the viewpoint of . Among all possible channel cross sections, the hydraulically efficient section is a semicircle since, for a given area, it has the minimum wetted perimeter. The proportions of the hydraulically efficient section of a specified geometric shape can be. The geometric elements of these sections are summarized in Table. It should be noted that, the hydraulically efficient section is not necessarily the most economic section.

In practice the following factors are to be kept in mind:

- The hydraulically efficient section minimizes the area required to convey a specified discharge. however, the area which required to be excavated to achieve the flow area required by the hydraulically efficient section may be much larger if one considers the removal of the over burden.
- It may not be possible to construct a hydraulically efficient stable section in the available natural condition. If the channel is to be lined, the cost of the lining may

be comparable with the cost of excavation.

- The cost of excavation depends on the amount of material that is to removed, in addition to. Further Topography of the land access to the site also influence the cost of disposal of the material removed.

a. The slope of the channel bed must be considered also as a variable since it is not necessarily completely defined by topographic consideration. For example, a reduced channel slope may require a larger flow area to convey the flow, on the other hand the cost of excavation of the overburden may be reduced.

2. Side slopes

The side slopes of a channel depend primarily on the engineering properties of the material through which the channel is excavated. From a practical viewpoint, the

side slopes should be suitable for prelimianary purposes. However, in deep cuts, side slopes are often steeper above the water surface than they would be in an irrigation canal excavated in the same material.In many cases, side slopes are determined by the economics of construction. In this regard following observations are made:

a. In many unlined earthen canals, side slopes are usually 1.5 : 1; However,

side slopes as steep as 1:1 have been used when the channel runs through cohesive materials.

b. In lined canals, the side slopes are generally steeper than in an unlined canal. If concrete is the lining material, side slopes greater than 1 : 1 usually require the use of forms, and with side slopes greater than 0 .75 : 1 the linings must be designed to withstand earth pressures. Some types of lining require side slopes as flat as those used for unlined channels.

c. Side slopes through cuts in rock can be vertical if this is desirable.

Table: Suitable side slopes for channels built in various types of materials (chow, 1959)

Material	Side slope
Rock	Nearly vertical
Muck and peat soils	1 / 4 : 1
Stiff clay or earth with concrete lining	1 / 2 : 1 to 1 : 1
Earth with stone lining or each for large channels	1 : 1
Firm clay or earth for small ditches	1 1/2 : 1
Loose,sandy earth	2 : 1
Sandy loam or porous clay	3 : 1

Indian standards for canal in cutting and embankment

	Side slope (Horizontal to Vertical m:1)	
Material (soil)	Cutting	Embankment
Hard clay or gravel	0.75 : 1	1.5 to 1.0
Soft Clay and alluvial soils	1.0 to 1.0	2.0 to 1.0
Sandy loam	1.5 to 1.0	2.0 to 1.0
Light sand	2.0 to 1.0	2.0 to 1.0 to 3.0 to 1.0
Soft rock	0.25 to 1.0 to 0.5 to 1.0	-
Hard rock	0.125 to 1 to 0.25 to 1.0	-

3. Longitudinal slope

The longitudinal slope of the channel is influenced by topography, the head required to carry the design flow, and the purpose of the channel. For example, in a hydroelectric power canal, a high head at the point of delivery is desirable, and a minimum longitudinal channel slope should be used. The slopes adopted in the irrigation channel should be as minimum as possible inorder to achieve the highest command. Generally, the slopes vary from 1 : 4000 to 1 : 20000 in canal. However, the longitudinal slopes in the natural river may be very steep (1/10).

Slope of the channels in Western Ghats

Gentle slope	10 m / km	$S_0 = 0.01$
Moderate slope	10 to 20 m / km	$S_0 = 0.01$ to 0.02
Steep slope	≥20 m / km	$S_0 \geq 0.02$

4. Permissible Velocities: Minimum and Maximum

It may be noted that canals carrying water with higher velocities may scour the bed and the sides of the channel leading to the collapse of the canal. On the other hand the weeds and plants grow in the channel when the nutrients are available in the water. Therefore, the minimum permissible velocity should not allow the growth of vegetation such as weed, hyacinth as well you should not be permitting the settlement of suspended material (non silting velocity).

"Minimum permissible velocity" refers to the smallest velocity which will prevent both sedimentation and vegetative growth in general. an average velocity of (0.60 to 0.90 m/s) will prevent sedimentation when the silt load of the flow is low.

A velocity of 0.75 m /s is usually sufficient to prevent the growth of vegetation which significantly affects the conveyance of the channel. It should be noted that these values are only general guidelines. Maximum permissible velocities entirely depend on the material that is used and the bed slope of the channel. For example: in case of chutes, spillways the velocity may reach as high as 25 m/s. As the dam heights are increasing the expected velocities of the flows are also increasing and it can reach as high as 70 m/s in exceptional cases. Thus, when one refers to maximum permissible velocity, it is for the normal canals built for irrigation purposes and Power canals in which the energy loss must be minimized. Hence, following table gives the maximum permissible velocity for some selected materials.

Maximum permissible velocities and n values for different materials

Material	V (m / s)	n
Fine sand	0.5	0.020
vertical Sandy loam	0.58	0.020
Silt loam	0.67	0.020

Firm loam	0.83	0.020
Stiff clay	1.25	0.025
Fine gravel	0.83	0.020
Coarse gravel	1.33	0.025
Gravel	1.2	
Disintegrated Rock	1.5	
Hard Rock	4.0	
Brick masonry with cement pointing	2.5	
Brick masonry with cement plaster	4.0	
Concrete	6.0	
Steel lining	10.0	

5. Resistance to the flow

In a given channel the rate of flow is inversely proportional to the surface roughness. The recommended values for a different types of lining are given below:

Manning roughness for the design of several types of linings is as follows

Surface Characteristics	Value of n
Concrete with surface as indicated below	
(a) Trowel finish	0.012 - 0.014
(b) Flat finish	0.013 - 0.015
(c) Float finish some gravel on bottom	0.015 - 0.017
(d) Gunite, good section	0.016 - 0.017
Concrete bottom float finished sides	as indicated below
(a) Dressed stone in mortar	0.015 - 0.017
(b) Random stone in mortar	0.017 - 0.020
(c) Cement rubble masonry plastered	0.016 - 0.020
Brick lining	0.014 - 0.017

Asphalt lining	
(a) Smooth	0.013
(b) Rough	0.016
Concrete lined excavated	rock with
(a) Good section	0.017 - 0.020
(b) Irregular section	0.022 - 0.027

These values should, however, be adopted only where the channel has flushing velocity. In case the channel has non-flushing velocity the value of n may increase due to deposition of silt in coarse of time and should in such cases be taken as that for earthen channel. The actual value of n in Manning formula evaluated on the basis of observations taken on Yamuna Power Channel in November 1971 ranged between 0.0175 and 0.0229 at km 0.60 and between 0.0164 and 0.0175 at km 2.05. The higher value of n evaluated at km 0.60 could be attributed to the deposition of silt in head reaches of the channel.

Table: Manning Roughness Coefficients

Lining Category	Lining Type	n-value different depth ranges		
		Depth ranges		
		0 – 15 cm	15 – 60 cm	> 60 cm
Rigid	Concrete	0.015	0.013	0.013
	Grouted Riprap	0.040	0.030	0.028
	Stone Masonry	0.042	0.032	0.030
	Soil Cement	0.025	0.022	0.020
	Asphalt	0.018	0.016	0.016
Unlined	Bare Soil	0.023	0.020	0.020
	Rock Cut	0.045	0.035	0.025
Temporary	Woven Paper Net	0.016	0.015	0.015
	Jute Net	0.028	0.022	0.019
	Fiberglass Roving	0.028	0.021	0.019
	Straw with Net	0.065	0.033	0.025
	Cured Wood Mat	0.066	0.035	0.028
	Synthetic Mat	0.036	0.025	0.021

Gravel Riprap	2.5-cm (d50)	0.044	0.033	0.030
	5 -cm (d50)	0.066	0.041	0.034
Rock Riprap	15-cm (d50)	0.104	0.069	0.035
	30-cm (d50)	-	0.078	0.040

Freeboard

The term freeboard refers to the vertical distance between either the top of the channel or the top of the channel is carrying the design flow at normal depth. The purpose of freeboard is to prevent the overtopping of either the lining or the top of the channel fluctuations in the water surface caused by wind - driven waves, tidal action, hydraulic jumps, super elevation of the water surface as the flow goes round curves at high velocities, the interception of storm runoff by the channel, the occurrence of greater than design depths of flow caused by canal sedimentation or an increased coefficient of friction, or temporary misoperation of the canal system.

There is no universally accepted role for the determination of free board since, waves, unsteady flow condition, curves etc., influence the free board. Free boards varying from less than 5% to 30% of the depth are commonly used in design. In semi-circular channels, when the velocities are less than 0.8 times the critical velocity then 6% of the diameter as free board have been proved to be adequate.

The freeboard associated with channel linings and the absolute top of the canal above the water surface can be estimated from the empirical curves. In general, those curves apply to a channel lined with either a hard surface, a membrane, or compacted earth with a low coefficient of permeability. For unlined channels, freeboard generally ranges from 0.3m for small laterals with shallow depths of flow to 1.2m for channels carrying 85 m^3 /s at relatively large depths of flow. A prelimimary estimate of freeboard for an unlined channel can be obtained from USBR formula.

$F_B = Cy$

in which F_B *is the freeboard in feet, y is the design depth of flow in feet,*

C is a coefficient. However, it may be noted that C has dimensions of $L^{1/2}$. C varies from 1.5 at Q = 0.57 m^3/s to 2.5 or canal capacity equal to and more than 85 m^3/s.

The free board recommended by USBR for channels are given below

Q m^3/s	Free board F_B in m
< 0.75	0.45
0.75 - 1.5	0.60
1.5 - 85.0	0.75
> 85	0.90

The free board (measured from full supply level to the top of lining) depends upon the size of canal, velocity of water, curvature of alignment, wind and wave action and method of operation. The normal free board is 15 cm for small canals and may range up to 1.0 m for large canals. The U.S.B.R. practice for the minimum permissible free board for various sizes of canal is given in Figure. Indian Standard IS : 4745 recommends a free board of 0.75 m for canal carrying a discharge of more than 10 m^3/sec.

Free board as per Indian Standards (IS 4745 - 1968), (IS 7112 - 1973)

Discharge Q (m^3/s)	Free board (m)	
	Unlined	Lined
< 10.0	0.50	0.60
> 10.0	0.75	0.75

Free boards provided in some of the major lined canals in India are given below

Sl.No.	Name of Canal	Free Board F_B in m
1	Yamuna Power Channel	0.75
2	Nangal Hydel Channel	0.76
3	Gandak Canal	0.45
4	Lower Ganga Canal (Link Canal)	0.30
5	Rajasthan Feeder Channel	0.76
6	Tungabhadra Canal	0.30
7	Mannaru Canal	0.30
8	Sunder Nagar Hydel Channel	0.91
9	Sarda Sahayak Feeder Channel	1.25

Actually adopted Free board for different ranges of discharge in India are below

Q (m^3/s)	< 0.15	0.15 - 0.75	0.75 - 1.50	1.50 - 9.00	> 9.00
Free board (m)	0.30	0.45	0.60	0.75	0.90

References to be noted

IS: 4745 - 1968, Code of practice for Design of Cross Section for Lined Canals, Indian Standards Institution, New Delhi, 1968.

IS: 7112 - 1973, Criteria for Design of Cross Section for Unlined Canals in Alluvial Soil, Indian Standards Institution, New Delhi, 1974.

When flow moves around a curve, a rise in the water surface occurs at the outer bank with a corresponding lowering of the water surface at the inner bank. In the design of a channel, it is important that this difference in water levels be estimated. If all the flow is assumed to move around the curve at the subcritical average velocity .

In India, the minimum radii of curvature are often longer than those used in the United States. For example, Some Indian engineers recommend a minimum radius of 91m for canals carrying more than 85 m^3/s (Houk, 1956). Suggested radii for different discharges are given in table below.

Radius of curves for lined canals

Discharge (m^3/s)	Radius (minimum) in m
280 and above	900
Less than 280 to 200	760
Less than 200 to 140	600
Less than 140 to 70	450
Less than 70 to 40	300

Note: Where the above radii cannot be provided, proper super elevation in bed shall be provided.

The width of the banks along a canal are usually governed by a number of considerations which include the size of the need for maintenance roads. Where roads are needed, the top widths for both lined and unlined canals are designed so that precipitation will not fall in to the canal water and, to keep percolating water below the ground level beyond the banks.

Hydraulically Efficient Channel

It is well known that the conveyance of a channel section increases with increases in the hydraulic radius or with decrease in the wetted perimeter. Therefore, from the point of hydraulic aspects, the channel section having the least wetted perimeter for a given area has the maximum conveyance; such a section is known as the Hydraulically efficient channel. But this is popularily referred as Best Hydraulic section. The semicircle has the least perimeter among all sections with the same area; hence it is the most hydraulically efficient of all sections.

The geometric elements of six best hydraulic section are given in Table. It may be noted that it may not be possible to implement in the field due to difficulties in construction and use of different materials. In general, a channel section should be designed for the best hydraulic efficiency but should be modified for practicability. From a practical point of view, it should be noted that a best hydraulic section is the section that gives the minimum area of flow for a given discharge but it need not be the minimum excavation. The section of minimum excavation is possible only if the water surface is at the level of the top of the bank. When the water surface is below the bank top of the bank (which is very common in practice), channels smaller than those of the best hydraulic section will give minimum excavation. If the water surface overtops the banks and these are even with the ground level, wider channels will provide minimum excavation. Generally, hydraulically efficient channel is adopted for lined canals. It may also be noted that hydraulically efficient channel need not be economical channel (least cost).

Design of Stable Unlined Channels

Erodible Channels which Scour but do not silt. The behaviour of flow in erodible channels is influenced by several parameters and precise knowledge is not available on various aspects. Unlined channels with channel bed and banks composed of earth, sand or gravel must be designed so that they maintain a stable configuration. There are three procedures.

Velocity based Method of maximum permissible velocity.

Regime Theory - Empirical equations for channels with equilibrium sediment throughput ("Live - Bed" equations).

Shear Based - Tractive force methods, Shield analysis.

Method of maximum permissible velocity also known as non-erodible velocity: It is

the highest mean velocity that will cause no erosion in the channel body.

When compared with the design process typically used for lined channels, the design of stable, unlined or erodible, earthen channels is a complex process involving numerous parameters, most of which cannot be accurately quantified. The complexity of the erodible channel design process results from the fact that in such channels stability is dependent not only on hydraulic parameters but also on the properties of the material which composes the bed and sides of the channel.

A stable channel section is one in which neither objectionable scour nor deposition occurs. There are three types of unstable sections: (USBR).

The pioneering work of Fortier and Scobey (1926) was the basis of channel design.

1. The banks and bed of the channel are scoured but no deposition occurs.

Example: When the channel conveys sediment free water (or water with only a very small amount of sediment) but with adequate energy to erode the channel.

2. Unstable channel with deposition but no scour.

Example: When the water being conveyed carries a large sediment load at a velocity that permits sedimentation.

3. Unstable channel with both scour and deposition occur.

Example: When the material through which the channel is excavated is susceptible to erosion and the water being conveyed carries a significant sediment load.

These types of channels can be designed using the method of maximum permissible velocity.

The following important points are to be noted.

1. First, the maximum permissible velocity is recommended for canals with a sinuous alignment.

2. Second, these data are for depths of flow less than 0.91 m . For greater depths of flow, the maximum permissible velocity should be increased by 0.15 m/s.