Gulley and Ravine Control Structures

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Module 1: Formation of Gully and Ravine

Lesson 1 Introduction

1.1 Soil Erosion and Its Causes

Land degradation is one of the most serious global challenges to sustainability of agriculture at present. It is temporary or permanent reduction in the productive capacity of land as a result of human action.

Watershed, a geographical area that contributes runoff to a common point, has been accepted as a basic unit for planning and implementation of the protective, curative and ameliorative programmes addressing land degradation. A thorough understanding of the hydrological behavior of a watershed is important for developing an effective watershed management plan and also for transferring the results of one watershed to another with similar characteristics (Tripathi and Panda, 1999).

Soil erosion is one of the most serious problems in the world. The problem of soil erosion is prevalent over about 53 % of the total land area of India. Soil erosion has caused major environmental disasters worldwide. Many urban and rural communities have been severely affected, while the sustainability of the total landscape has been threatened. Human and animal population, physical infrastructure, agricultural lands and socio economic system of the land/areas are adversely exposed to multifaceted hazards. Some of the adverse impacts of soil erosion are: (i) it removes fertile top soil rendering the eroded area poorly productive; (ii) it causes sedimentation of the downstream river reaches that in turn changes flow section, slows down the flow rate and increases pollution hazard; (iii) gradual deposition of silt at the downstream river reaches raises the river bed elevation and causes flood hazard; (iv) sedimentation of the reservoirs built across rivers reduces their live storage capacity, which adversely affects drinking water supply projects, irrigation projects and hydro-electric projects depending on the reservoir water; (v) silt deposit may give rise to river braiding and river meandering, which adversely impacts the river bank inhabitants, and (vi) soil erosion makes above-ground structures unsafe.

Soil erosion is a physical process with considerable variation globally in its severity and frequency. It is also strongly influenced by social, economic, political and institutional factors.

Soil erosion is a three-stage process:

(1) Detachment,

(2) Transport, and

(3) Deposition of soil.

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There are four principal sources of energy: physical, such as wind and water direct rainfall as well as flowing water); gravity, chemical reactions responsible for weathering of parent rocks to form soils and anthropogenic, such as faulty tillage operations or improper cropping practices. Soil erosion begins with detachment, which is caused by breaking down of aggregates by rain drop impact, sheer or drag force of water and wind. Detached particles are transported by flowing water (over-land flow and inter-flow) and wind, and deposited when the velocity of water or wind decreases due to the effect of slope or ground cover.

Three processes that accelerate the natural rate of soil erosion are:

(1) Dispersion,

(2) Compaction and

(3) Crusting,

These processes decrease structural stability, reduce soil strength, increase erodibility and intensify susceptibility to transport by overland flow, interflow, wind or gravity. These processes are accentuated by soil disturbance (i.e. by tillage, vehicular traffic), lack of ground cover (i.e. bare fallow, residue removal or burning) and harsh climate (i.e. high rainfall intensity and
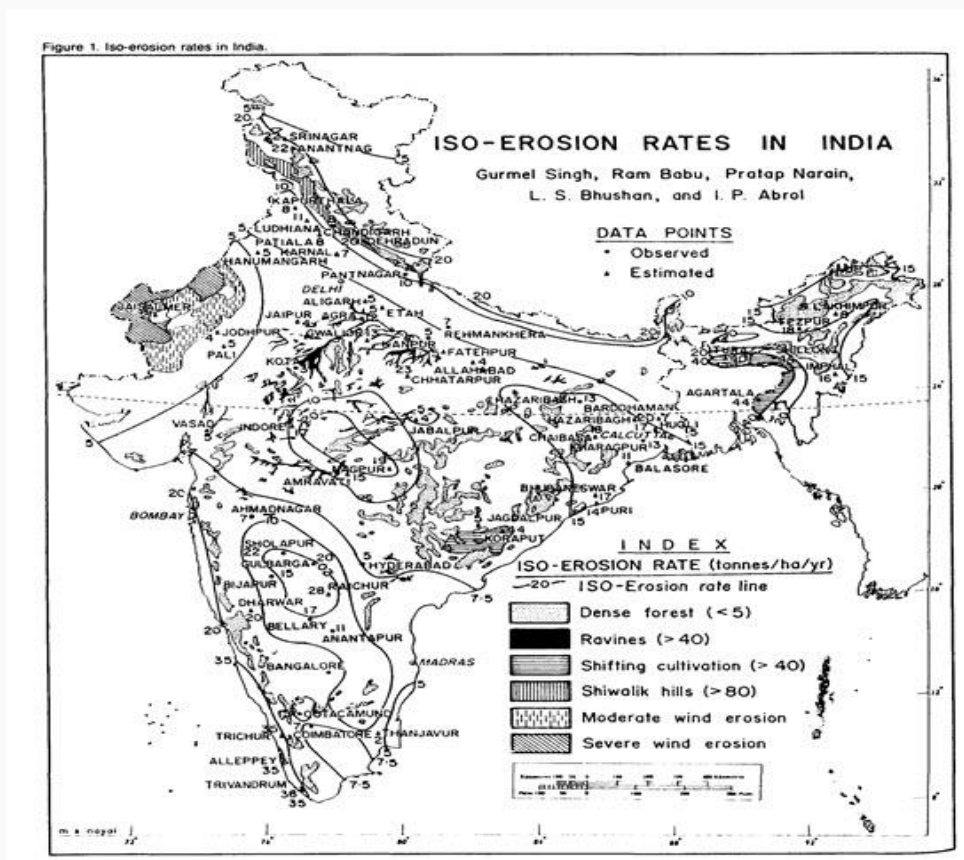

Fig.1.1. Soil erosion rates in India. (Source: http://www.ciesin.org/docs/002-413/002-413.html)

Causes of Erosion

Erosion occurs when farming practices are not compatible with the soil and land slope limitations such as non-cohesive soils and steeper land slopes that make the soil more prone to be washed away or blown away. These practices are:

- Overstocking and overgrazing

- Inappropriate farming techniques such as deep ploughing of land 2 or 3 times a year to produce annual crops

- Lack of crop rotation

- Planting crops along the slope instead of along the contour.

Fig. 1.1. Soil erosion. (Source: http://www.networlddirectory.com/images/blogs/10-2007/soil-erosion-2290.jpg)

1.2 Definition of Gully and Ravine

1.2.1 Gully Erosion

The gullies are linear incision channels of at least 0.3m width and 0.3m depth. Gully erosion creates either V- or U-shaped channels. Gullies are primarily formed by concentrated runoff converging towards lower points of the watershed. Thus, erosion occurring in these channels is known as concentrated flow erosion. Undulating fields cause runoff to concentrate in natural swales as runoff moves down slope in narrow paths in the form of channelized flow. A **swale** is a low tract of land, which is moist or marshy. It may be naturally occurring landscape or human-created. Continued gully erosion removes entire soil profiles in localized segments of the field. As gullies grow, more sediment is transported.

Gully erosion is the advance stage of channel or rill erosion in which the size of rill is enlarged which can not be smoothened by ordinary tillage implements. Process of gully formation follows sheet and rill erosion. Gully erosion produces channels larger than rills. These channels carry water during and immediately after rains.

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Gullies may also be developed from rills which are unchecked. Development of gullies also takes place by ruts or tracks formed by the movement of machineries, down the slope.

Fig. 1.2. Gully erosion. (Source:
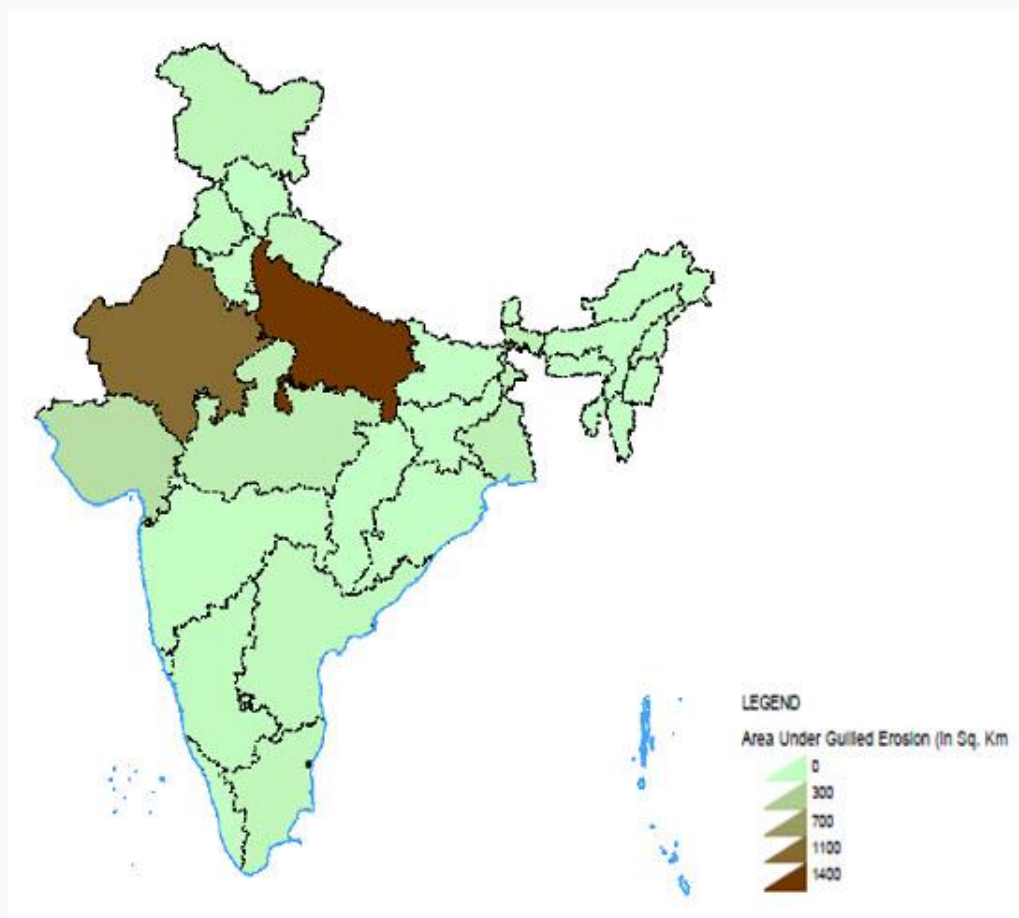**http://www.permacultureplants.net/NgareNdare/NgareNdareIntro.htm)**

Fig. 1.3. Total gullied erosion in India. (Source: Wasteland atlas of India) (Source:
http://www.soeatlas.org/PDF_Map%20Gallery/Gullied%20Erosion.pdf)

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The rate and extent of gully development are closely related to the amount and velocity of runoff water, since large amount of flowing water tends to detach and transport the soil in relatively larger amount. The amount of runoff water available is dependent upon the size and runoff producing charecterstics of the drainage area (watershed) involved. The amount of sediment from gully erosion is usually less than from upland areas. In tropical areas, gully growth following deforestation and cultivation has led to severe problems from soil loss, and damage to building, roads and airport. The rate of gully erosion depends primarily on the runoff-producing charecteristics of the watershed, the drainage area, soil charecterstics, the alignment, size and shape of the gully, and the slope in the chanel.

1.2.2 Ravine Erosion

A ravine is a very narrow, steep sided fissure in the Earth's surface. Ravines are smaller than valleys, but larger than gullies, although a ravine has the potential to develop into a valley, over the course of thousands of years. A ravine is generally a fluvial slope landform of relatively steep (cross-sectional) sides, of the order of twenty to seventy percent in gradient. Ravines may or may not have active streams flowing along the down slope channel which originally formed them. Moreover, often they are characterized by intermittent streams, since their geographic scale and their catchment areas may not be sufficiently large to support a perennial stream.
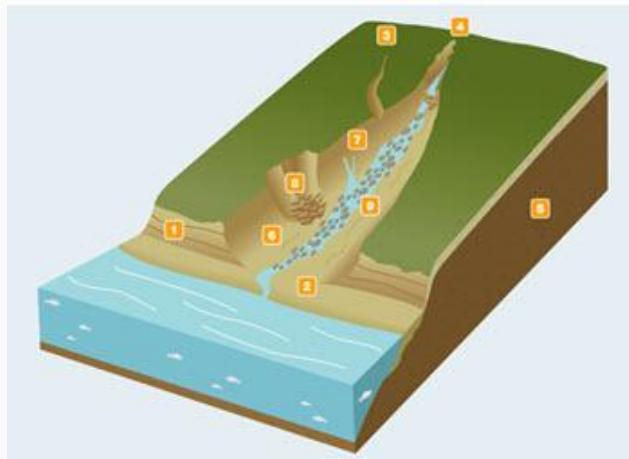
Fig. 1.3. Ravine erosion. (Source: http://wiki.fis-ski.com/images/Ravines.jpg)

Typically, a ravine is formed through the process of erosion, and it starts out as the site of a small stream or river. Over time, the water wears a deep groove into the Earth, which attracts water as it drains from other locations, speeding up the erosion process. Eventually, a ravine may lose its stream, or have only intermittent water flow, because of lack of water supply from the catchment. Sometimes, however, a ravine will have a year-round watercourse.

Generation of large quantities of waste water in the urban areas and a generally poor urban drainage promote the formation of ravines. It is common for water to collect in a large mass in urban areas, creating a torrent, because it cannot percolate naturally through the soil to drain away. Because the water eventually finds a path to flow under gravity, it can end up creating a cutting in periods of flooding and heavy rain, and this will develop into a ravine.

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Ravines have historically been used for garbage disposal, because of their depth and steep sides. Although this practice is largely discouraged today, ravines still tend to collect garbage, which is carried by the water which periodically pours through them as well as being tossed in by careless litterers. In urban areas, service organizations may designate a day each year to clean up local ravines, canyons, and waterways so that the garbage is not allowed to accumulate for too long.

Depending on the location of a ravine, it may also serve as habitat for local wildlife, especially in regions where wildlife is under pressure due to human habitation. Humans tend to avoid ravines, since they are difficult to navigate, and this allows a variety of creatures to move in and live undisturbed at the site. As a result, ravines are sometimes developed into habitations for birds and other forms of wildlife (http://www.wisegeek.com/what-is-a-ravine.htm).

Stages of Gully Erosion

The four recognised stages of gully development are given as under:

Stage1: In this stage channel erosion and deepening of the gully bed takes place. It is initiation stage and this stage normally proceeds slowly.

Stage 2: It is the development stage, in which due to runoff from up stream portion of the gully head, the size of gully width and depth is enlarged.

Stage 3: This is the healing stage, in which vegetation starts to grow in the channel. During this stage, there is no appericiable erosion in any form, from the gully section.

Stage 4: This is the last stage of gully development, in which gully is fully stablized. No further development of gully occurs, unless healing process is disturbed. The channel has a stable gradient and gully walls gain a stable slope and vegetation begins to grow in abundance to cover the soil surface.
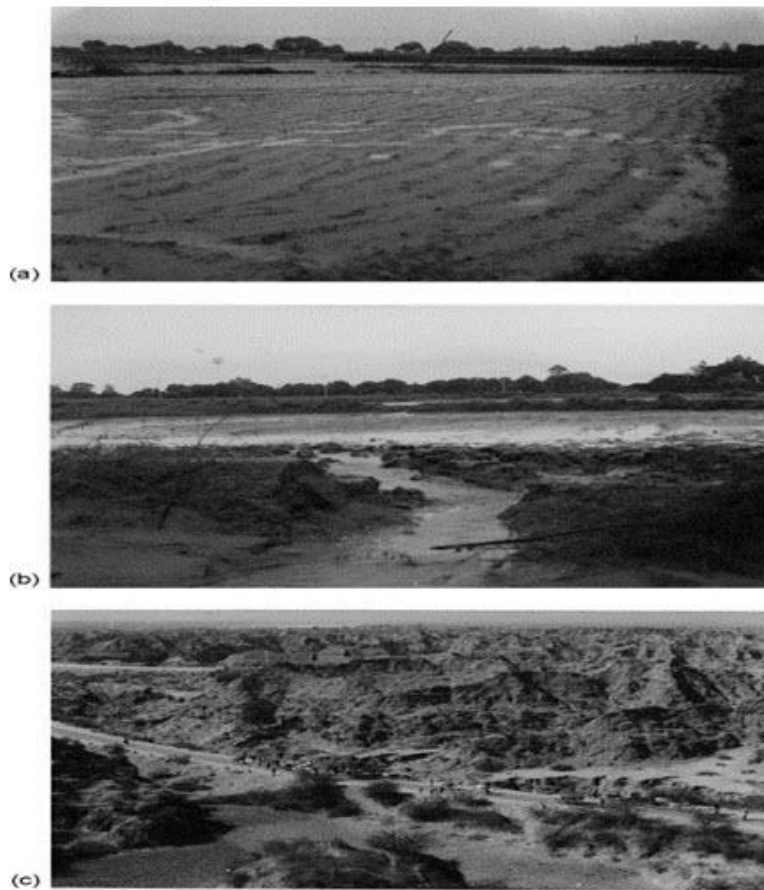
Fig. 1.4. (a) Initial stage of land degradation, i.e. wash off erosion in cultivated field, depicting concentration of flow inducing incarnation of rill. (b) Runoff causing gully head cut at the point of vertical fall, beginning of severe land degradation. (c) Severely degraded ravine waste land in the Yamuna Chambal ravinous belt. (Source: http://www.sciencedirect.com/science/article/pii/S0378377402001580)

Classification of Gully: Gullies are classified as follows:

1) Based on Shape of the Gully: Gullies are classified into the following two shapes:

a) U-Shaped

Generally found in the alluvial plains, where surface and sub-surface soils are easily erodible. The specific features of these gullies are:

- U-shaped cross-section

- Longitudinal slope of gully bottom is usually parallel to the slope of the land, through which the gully passes.

- The runoff contributing catchment area being large, the discharge passing through these gullies is large.

- The velocity of flow is relatively lower than that of the V-shaped gullies.

- U-shaped gullies continue to grow headward.

- The lateral spacing of these gullies is large.

- Active erosion in these gullies, is from side banks and the gully head as a result of undercutting at these at the base of vertical cut.

- These gullies do not grow deeper, but becomes wider and longer, progressing headward.

b) V-shaped

The V-shaped gullies are often developed where the sub-soils are tough enough to resist the rapid cutting of soil by the runoff. As resistence to erosion increases with depth, the width of cut decreases accordingly and results in development of V-shaped gully.

V-shaped gullies have the following major features:

- V-shaped cross-section.

- Generally appear on sloping field.

- Longitudinal gradient of channel is greater than the land slope.

- Catchment area contributing the runoff is small.

- The lateral spacing between these gullies is small.

- Tha amount of discharge, passing through these gullies is small but has higher velocity.

- The V-gullies make the contour cutivation difficult.

- V-shaped gullies often devlop from rill erosion, when water is concentrated from several rills into one.

The shape of the gully depends upon the soil characterstics, climatic conditions, age of the gully and the types of erosion.

2) Based on State of the Gully

Gullies can be classified into the following types:

i. Active Gullies: active gullies are those, whose dimensions are enlarged with time. The size enlargement is based on the soil charecterstics, land use and volume of runoff passing through the gully. The gullies found in plain area is active.

ii. Inactive Gullies: dimension do not appreciably change with time. These gullies found in rocky areas, are inactive because rocks are resistant to erosion by the runoff flow.

3) Based on Dimensions of Gully

Gullies are clasified based on their size as:

i. Small Gullies, can be easily crossed by farm implements and can also be smoothened by ploughing and other land development operations and by stablizing them through vegetation.

ii. Medium Gullies, can not be easily crossed by farm implements. They can be controlled by terrecing or ploughing operations. In medium gullies, the sides are stablized by promoting vegetative growth on them.

iii. Large Gullies: these gullies can not be reclaimed. For controlling these tree plantation is done as an effective measure.

1.3 Causes of Gully Erosion

There are two types of causes to activate the gully formation:

a) Natural Causes

- Rainfall

- Runoff

- Flood

- Soil Properties

- Vegetative Cover

b) Anthropogenic Causes

- Creating land surface without vegetation.

- Road construction

- Adoption of faulty tillage practices.

- Overgrazing and other form of biotic pressure on the vegetative cover, existing on the land surface.

- Absence of vegetative cover.

- Improper construction of water channels, roads, rail lines, cattle trails etc.

Effect of Gully Erosion

- Loss of soil productivity

- Adverse effect on other water resource facilities

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- Loss of reservoir storage capacity

- Flood impacts

- Recreational impacts

- Deterioration of water quality

1.4 Introduction to Control Measures

Gullies are formed by excessive surface runoff, flowing with high velocity and force that are sufficient to detach soil particles and carry away them along the runoff flow path. Gully and channel erosion frequently occur because of increased water flowing from denuded areas. The runoff can start from bare land, faulty drainage, farm roads, neglected rills and furrow in farm field or from clogged drainage canals.

For controlling gully erosion, the following considerations are very important:

- Improving the catchment area of the gully

- Stabilization of gully head

- Safely conduct water through the gully, provided that it is not a part of natural drainage system of the area

- Adoption of gully control measures to stabilize them

Gully Control Measures

1. **Control by Vegetation:** vegetaion provides soil cover and protect the gully against scouring. It also reduces the flow velocity by increasing the hydraulic ressistance of the channel section, thereby the scouring and ability of runoff is reduced to a great extent.

2. **Control by Structures:** structures are used to control the flow velocity. Structures are of two types:

A) Temporary Structures: temporary structures are constructed to serve the following purposes:

- To collect sufficient amount of soil on their upstream portion to build up a huge growth of vegetative cover.

- To check the gully erosion until sufficient vegetation has been established at the critical points of gully.

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Temporary Structures are:

1) Brushwood dam:

- Single row brushwood dam

- Double row brushwood dam

2) Loose rock fill dam

3) Log check dam

4) Netting dam

5) Staggered trenches or bunds

6) Terraces (there are stable permanent terraces also used for crop cultivation)

7) Grassed water ways

B) Permanent structures: These structures are made of permanent materials such as: masonary, reinforced concrete or earth etc.

For the purpose of gully control, the following types of permanent structures are used:

1) Spillway:

a) Drop inlet spillway

b) Straight drop spillway

c) Chute spillway

2) Rubble masoonary dam

3) Concrete dam

4) Gabions

5) Silt trap dam

1.5 Organizations in India dealing with Soil Conservation Related Issues

1) Central Arid Zone Research Institute, Jodhpur, Rajsthan

2) Central Institute Brackishwater Aquaculture, Chennai, Tamilnadu

3) Central Institute of Arid Horticulture, Bikaner, Rajsthan

4) Central Research Institute of Dryland Agriculture, Hyderabad, Andhra Pradesh

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5) Central Soil and Water Conservation Research and Training Institute, Dehradun, Uttrakhand

6) Central Soil Salinity Research Institute, Karnal, Haryana

7) ICAR Research Complex for Eastern Region including Centre of Makhana, Patna, Bihar

8) Indian Institute of Soil Sciences, Bhopal, Madhya Pradesh

9) National Bureau of Soil Survey and Land Use Planning, Nagpur, Maharastra

10) Damodar Valley Corporation, Hazaribagh, Jharkhand

11) Central Water Commission, Govt. of India

Lesson 2 Extent of Gully and Ravine Erosion Problem

2.1 Extent of Gully and Ravines in India

Gully erosion has been described in a large variety of landscapes throughout the world. In simple terms, gullies may be described as continuous depression on the sloping land surface as a result of soil displacement caused by overland water flow and aided by gravity force. They may extend in length from a few meters at the initiation stage and up to hundreds of meters, if the erosion is not checked. The commonly accepted definition of gullies is that they are larger than rills, which can be ploughed or easily crossed but smaller than streams, creeks, or river channels. The most commonly described gullies are the 'hillslope gullies', which are present in the upland portions of catchments. Gully erosion and the associated soil loss have caused major environmental disasters worldwide. Many urban and rural communities have been severely affected, while the sustainability of the total landscape has been threatened. Human and animal population, physical infrastructure, agricultural lands and socio economic system of the land/areas are adversely exposed to multifaceted hazards. In many developing countries, several villages and communities have been displaced and virtually disappeared as a result of the scourages of gully erosion.

Sheet erosion, consisting of the washing away of the fertile top layers of the soil, is the most extensive form of erosion that occurs even on moderately sloping lands. It causes enormous losses to agriculture every year by reducing the productive capacity of lands. Gully erosion, which generally starts after sheet erosion has remained unchecked for some time, has already rendered large areas useless, and is steadily increasing. Ravines are a result of formation of gullies within unconsolidated, relatively loosely bound material such as soft sediments.

India accounts for a meager 2.4 per cent of the world surface area of 135.79 million sq. km. It covers an area of 3,287,263 sq. km., extending from the snow covered Himalayan heights in the North to the tropical rain forests of the South. Although ravines and gullies occur all over India, the largest incidence is found in Madhya Pradesh, Uttar Pradesh and parts of Rajasthan. Ravines are spread over an estimated area of 3.67 million hectares along the rivers and their tributaries. The National Remote Sensing Agency, based on the Landsat data, has estimated nearly 4 million hectares of ravine land. Serious ravine intrusions occur along the banks of Beas in Punjab; Chambal in Madhya Pradesh, Rajasthan and Uttar Pradesh; Kalisind, Banas, Morel and Gambhir in Rajasthan; Yamuna in Uttar Pradesh; Mahi, Sabarmati, Narmada and Tapti in Gujarat.

Wasteland categories, described though different types of associated problems undergo some changes from time to time to make the information more up-to-date and more comprehensive. This is shown in Table 2.1.

Table 2.1. Comparison of wastelands categories during 2003 and 2005-2006:

S. No.	Classes of 2003 Database	Classes of 2005-2006 Database
01.	Gullied and Ravinous Land – Shallow	Merged with Gullied and Ravinous Land – Moderate
02	Land Affected by Salinity / Alkalinity – Slight	Merged with Land affected by Salinity / Alkalinity – Moderate
03.	Sands – a. Flood Plains b. Levees	Merged with Sandy Area – Riverine
04.	Sands Desertic a. Sands – Semi-stabilized to stabilized – low b. Closely spaced Inter-dunal area	Merged with Sandy Area – Desertic
05.	Steep sloping Area	Merged with Barren Rocky / Stony Waste Area

(Source: Degraded and Wastelands of India: Status and Spatial Distribution, 2010, Indian Council of Agricultural Research, New Delhi)

In India, land degradation poses problem mainly to agriculture and also to some other sectors such as housing, town planning, etc. To enable the use of the degraded lands, some mitigation measures are invariably required to be adopted. The statistics of variously degraded lands in the world are given in Fig. 2.1. Figure 2.2 shows the gully eroded lands in India. In some cases, mitigation measures may not be feasible such as in snow-covered lands (Fig. 2.3).
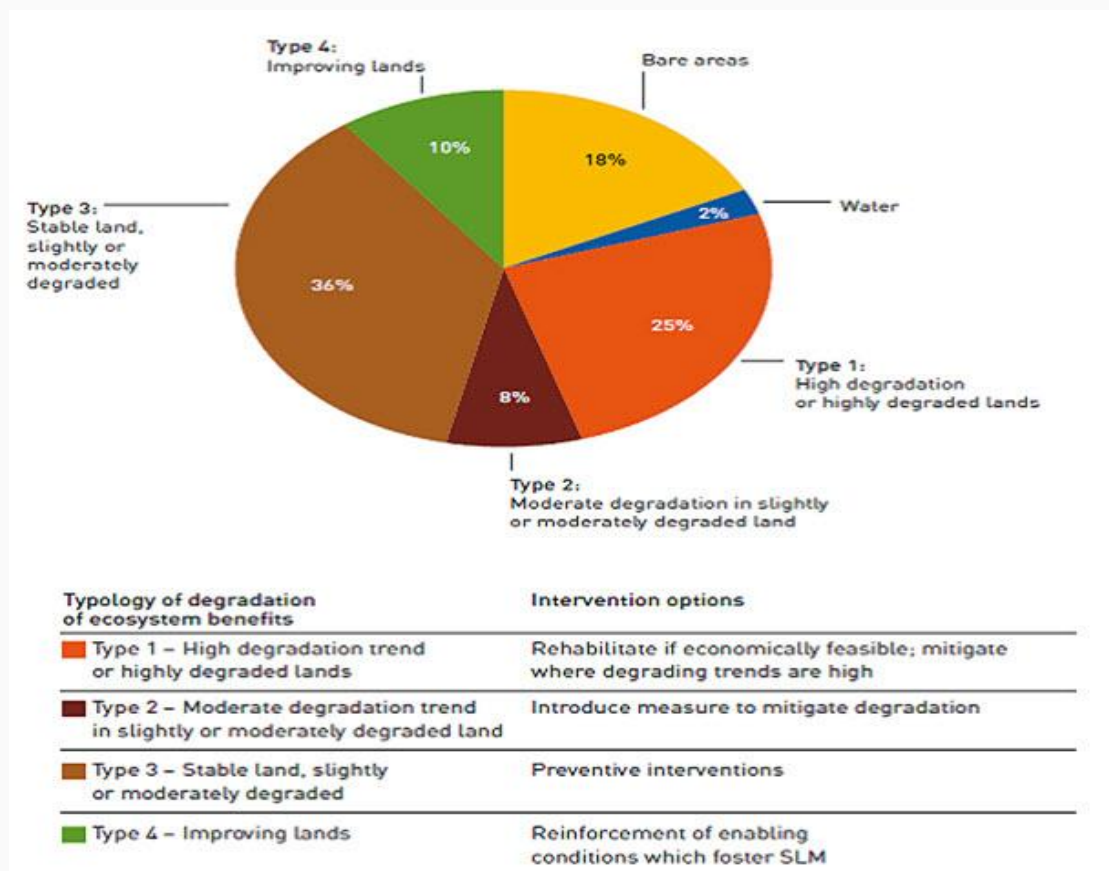
Fig. 2.1. Classification of Degraded Areas of the world of the world. (Source: http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/SOLAW_thematic_report_3_land_degradation.pdf)

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Land use and land cover has become increasingly important as the Nation plans to overcome the problems of haphazard, uncontrolled development, deteriorating environmental quality, loss of prime agricultural lands, and destruction of important wetlands. Land use data are needed in the analysis of environmental processes and problems that must be understood if living conditions and standards are to be improved or maintained at current levels. Table 2.2 shows the land use classification In India as surveyed and reported by Ministry of Agriculture.

Table 2.2. Land Use Classification in India (2005-2006)

Classification	2000-01	2001-02 (P)	2002-03 (P)	2003-04 (P)	2004-05 (P)	2005-06 (P)
1	2	3	4	5	6	7
I. Geographical Area	328.73	328.73	328.73	328.73	328.73	328.73
II. Reporting Area for Land Utilisation Statistics (1 to 5)	305.08	305.01	305.24	305.32	305.23	305.27
1. Forests	69.62	69.51	69.64	69.67	69.67	69.79
2. Not Available for Cultivation (a+b)	41.55	41.78	42.08	42.23	42.30	42.51
(a) Non Agricultural Uses	23.81	24.07	24.28	24.66	24.72	25.03
(b) Barren and Unculturable Land	17.74	17.71	17.80	17.57	17.58	17.48
3. Other Uncultivated Land excluding fallow Land(a+b+c)	27.71	27.37	27.41	26.98	27.00	26.92
(a) Permanent Pastures and Other Grazing Land	10.83	10.59	10.51	10.45	10.43	10.42
(b) Land Under Miscellaneous Tree Crops and Groves not Included in Net Area Sown	3.32	3.37	3.36	3.39	3.38	3.38
(c) Culturable Wasteland	13.56	13.41	13.54	13.14	13.19	13.12
4. Fallow Land (a+b)	25.03	24.94	33.46	25.48	24.94	24.17
(a) Fallow Land Other Than Current Fallows	10.19	10.30	11.76	11.20	10.72	10.50
(b) Current Fallows	14.84	14.64	21.70	14.28	14.22	13.67
5. Net Area Sown (6-7)	141.16	141.42	132.66	140.95	141.32	141.89
6. Gross Cropped Area	185.70	189.75	175.66	190.37	190.91	192.80
7. Area Sown More Than Once	44.54	48.33	43.00	49.42	49.59	50.90
8. Cropping Intensity*	131.60	134.20	132.40	135.10	135.10	135.90
III. Net Irrigated Area	54.84	56.30	53.88	56.00	58.54	60.20
IV. Gross Irrigated Area	75.82	78.07	72.89	77.11	79.51	82.63

P   : *Provisional*

*   : *Cropping Intensity is obtained by dividing the gross cropped area by the net area sown.*

Note   : *The decline in net area sown in 2002-03 reflects the impact of the severe drought of 2002-03 on agriculture operations.*

(Source: Agricultural Statistics at a Glance 2008, Ministry of Agriculture)

Figure 2.4 reveals that in India, the largest extent of land degradation occurs due to water erosion, followed by chemical problems of soil salinity, alkalinity and acidity and then by water logging. Besides natural water logging in high rainfall flat terrains, considerable water logging of agricultural lands takes place in the irrigation command areas, due to improper irrigation water management in water conveyance, distribution and application.

Fig. 2.4. Extent of Various Kinds of Land Degradation in India. (Source: State of Environment Report India-2009, Ministry of Environment & Forests, Government of India)

The soil degradation class based on area derived from 1: 250,000 soil map reveals that water erosion is the major problem in India and its effect on top soil is quite significant in comparison to other class of degradation, as shown in Table 2.4.

Table 2.4. NBSS&LUP soil degradation classes, derived from 1: 250,000 soil map (1985–1995)

Classes	Codes	Area (in M ha)
Water Erosion	W	
Loss of top-soil	Wt	83.31
Terrain deformation	Wd	10.37
Wind Erosion	E	
Loss of top-soil	Wt	4.35
Loss of top-soil/terrain deformation	Et/Ed	3.24
Terrain deformation/overblowing	Ed/Eo	1.89
Chemical Deterioration	C	
Salinization	Cs	5.89
Loss of nutrients (En) – (Acid soils)	En	16.03
Physical Deterioration	P	
Waterlogging	Pw	14.29
Others		
Ice caps/Rock outcrops/Arid mountain	I/R/M	8.38
Total		147.75

(Source: Degraded and Wastelands of India Status and Spatial Distribution, 2010, Indian Council of Agricultural Research New Delhi)

Wasteland map categories based on the area (M ha) gives the percentage of the area, according to surveyed total wasteland area of 63.85 M ha. Land without scrub (bare land) is more affected by erosion as shown in Table 2.5.

Table 2.5. Common categories of wasteland map (NRSA) and soil degradation map (NBSS&LUP)

Wasteland class	Area (in M ha)	Percentage
Gullied/ravinous land	2.06	0.65
Land with/without scrub	19.40	6.13
Waterlogged/marshy land	1.66	0.52
Land affected by salinity	2.04	0.65
Shifting cultivation area	3.51	1.11
Degraded notified forest land	14.07	4.44
Degraded pastures/grazing land	2.60	0.82
Degraded land under plantation	0.58	0.18
Sandy area	5.00	1.58
Mining/industrial wasteland	0.12	0.04
Barren rocky/stony/sheet rock	6.46	2.04
Steep sloping area	0.77	0.24
Snow covered/glacial area	5.58	1.76
Total	63.85	20.16

Note: Total wastelands are estimated at 63.85 M ha, correlating with strong, extreme and part of moderates categories of land degradation
Source: NRSA and MoRD. 2000

(Source: Degraded and Wastelands of India Status and Spatial Distribution, 2010, Indian Council of Agricultural Research New Delhi)

Table 2.6 shows that snow covered glacial areas are more degraded than gullied and ravine land as shown in soil degradation map (1986-2000). Water logging problem is also higher than other form of degradation.

Table 2.6. NRSA wasteland classes (1986–2000)

Wasteland map (1986–2000)	Area (in M ha)	Soil degradation map (1986–1995)	Area (in M ha)
Gullied and ravinous land	2.06	Terrain deformation (includes agricultural land)	10.37
Land affected by salinity/alkalinity	2.04	Salinization (including slight salinity category)	5.89
Waterlogging	1.66	Waterlogging (including sub-surface waterlogging)	14.29
Snow-covered glacial area	5.58	Ice caps	4.10
Total	11.34	Total	34.65

Source: NRSA and NBSS&LUP

(Source: Degraded and Wastelands of India Status and Spatial Distribution, 2010, Indian Council of Agricultural Research New Delhi)

Statistic of degraded land are given in Table 2.7 based on land use, which conveys that water erosion and wind erosion affect mainly agricultural class due to loss of top soil and gully formation as found in mainly wasteland. Land degradation due to acidity is also high due to

chemical in agricultural areas. Water logging is a severe problem which contributes 40.16 M ha in the form of physical degradation.

Table 2.7. Preliminary area statistics of degraded and wastelands of India

Degradation type	Area² (in M ha)	Land use
Water Erosion		
Loss of top-soil	13.25	Mainly agricultural areas
Gully formation	8.31	Mainly wastelands and partly agriculture
Ravines	2.06	Mainly wastelands
Wind Erosion		
Loss of top soil	3.76	Mainly agricultural areas
Over blowing	1.89	Partly agriculture and partly wastelands
Terrain deformation	3.24	Mainly wastelands
Chemical Degradation		
Salt-affected soils	6.73	Partly agricultural and partly wastelands
Land degradation due to acidity	16.03	Mainly agriculture areas and partly wastelands
Physical Degradation		
Waterlogging		
Surface ponding	1.66	Mainly wastelands
Subsurface waterlogging	4.75	Mainly agricultural areas
Vegetal Degradation with Water Erosion	40.16	Mainly wastelands
Others		
Mining and industrial waste	0.13	Wastelands
Barren rocky/stony waste	6.46	Wastelands
Snow covered area/ice caps	5.58	Wastelands
Total area	114.01	

Notes: **1.** Statistics encompasses degraded lands in agricultural areas and wastelands; **2.** The results given in this table are preliminary, and are based on the incomplete information. Further studies on the harmonization of the area statistics were taken up inter-institutionally, which are given in Chapter 4

(Source: Degraded and Wastelands of India Status and Spatial Distribution, 2010, Indian Council of Agricultural Research New Delhi)

2.2 State-wise Affected Areas

State- wise degradation of land areas are given in the Table 2.8 and Table 2.9, in which degradation areas are divided into moderate, moderate severe, severe, very severe, extreme severe. It shows that Madhya Pradesh is having largest degraded area (km²) but the percentage of degraded area is high in Nagaland. Total percentage of degraded land of India is 39%. In Table 2.9 degraded lands are divided into two parts based on pH for water and wind erosion.

(a) 1- 9, for acid soil

(b) 10 - 19, for sodic soil

Table 2.8. State (region)-wise degraded land areas

State	TGA (km²)	Moderate [10-15] (tonnes/ha/yr)		Mod.Severe [15-20] (tonnes/ha/yr)		Severe [20-40] (tonnes/ha/yr)		Very Severe [40-80] (tonnes/ha/yr)		Extr.Severe [>80] (tonnes/ha/yr)		Total area for different classes (km²)	Area (%)
		Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)		
Andhra Pradesh	275,045	36,196	13	20,738	8	34,381	13	17,960	7			109,275	40
Arunachal Pradesh	83,743	4,271	5	4,539	5	19,805	24	22,870	27	9,354	11	60,839	73
Asom	78,438	3,592	5	14,182	18	11,632	15	22,198	28			51,604	66
Bihar	94,163	5,855	6	3,223	3	2,566	3	545	1			12,189	13
Chhattisgarh	134,805	10,771	8	8,695	6	24,561	18	18,360	14	25,640	19	88,028	65
Delhi	1,483	136	9	78	5	98	7	17	1			330	22
Gujarat	166,024	13,722	8	5,881	3	9,801	5	1,960	1			31,364	16
Haryana	44,212	1,136	3	553	1	809	2	420	1			2,918	7
Himachal Pradesh	55,673	3,023	5	2,088	4	4,120	7	3,196	6	5,612	10	18,038	32
Jammu and Kashmir	222,236	1,400	1	1,178	1	3,689	2	6,067	3	22,690	10	35,024	16
Jharkhand	79,714	12,424	16	9,140	11	16,739	21	9,748	12	3,699	5	51,750	65
Karnataka	191,791	51,784	27	21,097	11	17,261	9	3,836	2			93,978	49
Kerala	38,863	3,968	10	1,007	3	917	2	35	0			5,927	15
Madhya Pradesh	308,641	39,876	13	29,413	10	58,426	19	28,734	9	26,420	9	182,870	59
Maharashtra	307,713	30064	10	17,663	6	25,202	8	15,078	5	17,263	6	105,269	34
Manipur	22,327	3,405	15	2,552	11	5,941	27	0				11,898	53
Meghalaya	22,429	3,315	15	2,290	10	5,888	26	3,109	14	2,871	13	17,472	78
Nagaland	16,579	678	4	630	4	2,646	16	4,722	28	5,793	35	14,468	87
Orissa	155,707	16,007	10	10,417	7	14,854	10	6,571	4	1,619	1	49,468	32
Punjab	50,362	1,269	3	453	1	901	2	745	1			3,369	7
Rajasthan	342,239	26,250	8	15,811	5	27,790	8	13,347	4	6,571	2	89,769	26
Sikkim	7,096	64	1	84	1	555	8	776	11	1,137	16	2,616	37
Tamil Nadu	130,058	14,020	11	6,048	5	5,397	4	195	0			25,660	20
Tripura	10,486	745	7	734	7	682	7	902	9	965	9	4,027	38
Uttar Pradesh	238,568	66,480	28	23,984	10	19,910	8	32,397	13			142,772	59
Uttarakhand	55,845	4,114	8	3,757	6	4,931	9	18,267	33			31,069	58
West Bengal	88,752	10,553	12	3,763	4	3,257	4	346	0			17,919	20
Total	3,222,922	365,118	258	209,998	167	322,760	282	232,401	236	129,633	145	1,259,910	39

Note: *, Andaman and Nicobar Islands, Goa and Mizoram have not been evaluated
Sources: NBSS&LUP and CSWCR&TI

(Source: Degraded and Wastelands of India Status and Spatial Distribution, 2010, Indian Council of Agricultural Research New Delhi)

Table 2.9. State wise area statistics of degraded and wastelands of India

State	TGA (km²)	Degraded and wastelands classes* ('000 ha)								
		1	2	3	4	5	6	7	8	9
Andhra Pradesh	275,045	8,050	814	0	0.28	0	0	56	4	0
Andaman and Nicobar Islands	8,249	0.00	0	0	0.00	0	0	71	0	0
Arunachal Pradesh	83,743	165	215	300	501	968	0	0	0	0
Asom	78,438	1,929	437	411	1,319	265	0	0	0	0
Bihar	94,163	820	229	19	22	0.00	0	39	1	0
Chhattisgarh	134,805	2,347	75	812	1,383	147	0	0	0	0
Delhi	1,483	28	0	0	0	0	0	0	0	0
Goa	3,702	1	0	103	0	0	0	0	0	0
Gujarat	196,024	979	32	0	0	0	1	1,495	4	0
Haryana	44,212	303	0	2	0	0	0	44	2	0
Himachal Pradesh	55,673	941	43	34	41	1	0	0	0	0
Jammu and Kashmir	222,236	1,327	674	21	42	15	0	0	0	0
Jharkhand	79,714	2,825	356	226	394	115	0	0	0	0
Karnataka	191,791	7,450	349	69	24	0	0	2	0	0
Kerala	38,863	112	5	1,961	378	87	0	1	0	20
Madhya Pradesh	308,641	11,881	1,584	121	332	29	0	0	0	0
Maharashtra	307,713	8,400	422	41	228	0	0	164	7	0
Manipur	22,327	36	114	115	86	1,396	0	0	0	0
Meghalaya	22,429	127	579	52	175	796	0	0	0	0
Mizoram	21,081	0	0	150	0	1,013	0	0	0	0
Nagaland	16,579	1	30	17	45	1,454	0	0	0	0
Orissa	155,707	2,176	1,152	107	51	45	0	131	0	0
Punjab	50,362	228	74	0	0	0	0	0	0	0
Rajasthan	342,239	7,436	1,196	0	0	0	11,419	74	8	0
Sikkim	7,096	2	0	2	43	13	0	0	0	0
Tamil Nadu	130,058	2,063	71	161	216	50	0	10	1	0
Tripura	10,486	26	48	101	83	525	0	0	0	0
Uttar Pradesh	238,566	12,370	514	0	0	0	0	9	13	0
Uttarakhand	55,845	829	180	13	189	198	0	0	0	0
West Bengal	88,752	1,167	97	240	165	13	0	408	0	0
Others**	1,248							125		
Total	3,287,270	74,020	9,290	5,080	5,720	7,130	11,420	2,630	40	20

(continued)

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10	11	12	13	14	15	16	17	18	19	Total area of 1–19 classes ('000 ha)	State
			Degraded and wastelands classes* ('000 ha)								
0	0	17	154	39	0	0	1	39	19	9,193	Andhra Pradesh
0	0	0	0	0	0	0	0	0	0	71	Andaman and Nicobar Islands
0	0	0	0	0	0	0	0	0	5	2,154	Arunachal Pradesh
0	0	0	0	0	0	0	0	0	210	4,571	Asom
0	0	5	98	8	0	0	0	2	128	1,371	Bihar
0	0	0	10	3	0	0	0	7	0	4,784	Chhattisgarh
0	0	0	0	0	0	0	0	0	0	28	Delhi
0	0	0	0	0	0	0	0	12	6	122	Goa
0	60	0	545	0	0	0	0	12	1	3,129	Gujarat
0	0	0	183	1	0	0	0	12	4	551	Haryana
0	0	0	0	0	0	0	0	1	4	1,065	Himachal Pradesh
0	0	0	0	0	0	0	0	1	14	2,094	Jammu and Kashmir
0	0	0	0	0	0	0	0	21	6	3,943	Jharkhand
0	0	0	97	48	0	0	0	51	3	8,093	Karnataka
0	0	1	0	0	0	0	0	1	43	2,608	Kerala
0	0	0	74	49	0	1	0	24	0	14,095	Madhya Pradesh
0	0	0	256	164	0	0	1	16	27	9,728	Maharashtra
0	0	0	0	0	0	0	0	0	21	1,768	Manipur
0	0	0	0	0	0	0	0	0	3	1,732	Meghalaya
0	0	0	0	0	0	0	0	0	0	1,163	Mizoram
0	0	0	0	0	0	0	0	0	3	1,550	Nagaland
0	0	6	0	0	0	0	0	8	46	3,722	Orissa
0	0	0	151	1	0	0	0	6	34	494	Punjab
110	0	0	108	26	30	1	16	0	0	20,424	Rajasthan
0	0	0	0	0	0	0	0	0	0	60	Sikkim
0	0	2	305	28	0	17	2	34	37	2,997	Tamil Nadu
0	0	0	0	0	0	0	0	0	25	785	Tripura
0	0	0	626	692	0	2	0	3	176	14,405	Uttar Pradesh
0	0	0	0	0	0	0	0	1	25	1,435	Uttarakhand
0	0	0	0	0	0	0	0	7	43	2,140	West Bengal
										125	Others**
110	60	30	2,610	1,060	30	20	20	260	860	120,402	Total

Notes: Classes*: **1** Exclusively water erosion (>10 tonnes/ha/yr); **2** Water erosion under open forest; **3** Exclusively acid soils (*p*H <5.5); **4** Acid soils under water erosion; **5** Acid soils under open forest; **6** Exclusively wind erosion; **7** Exclusively saline soils; **8** Eroded saline soils; **9** Acid saline soils; **10** Saline soils under wind erosion; **11** Saline soils under open forest; **12** Waterlogged saline soils; **13** Exclusively sodic soils; **14** Eroded sodic soils; **15** Sodic soils under wind erosion; **16** Sodic soils under open forest; **17** Eroded sodic soils under open forest;**18** Mining/Industrial waste; **19** Waterlogged area (Permanent)
Others**: Chandigarh, Dadar and Nagar Haveli, Daman and Diu, Lakshadweep and Puducherry
Source: NBSS&LUP

(Source: Degraded and Wastelands of India Status and Spatial Distribution, 2010, Indian Council of Agricultural Research New Delhi)

Lesson 3 Soil Erosion

3.1 Introduction

Soil erosion is slow and gradual removal of fertile top soil caused by overland flow on sloping lands. It is initiated by formation of rills, followed by gullies, encroachment of desert due to wind effect and erosion of river banks. These have caused major land degradation worldwide.

There are two major types of erosion: geologic and accelerated erosion. Geologic erosion is a natural process of weathering that generally occurs at low rates on the parent rocks as the natural soil-forming processes. It occurs over long geologic time horizons and is not influenced by human activity. Some idea of the 'geologic time' can be formed from the fact that a measurable depth of a few centimeters of soil takes thousands year to form due to weathering of parent rocks. Accelerated erosion occurs due to anthropogenic causes such as deforestation, slash-and-burn agriculture, intensive plowing, intensive and uncontrolled grazing, and biomass burning. These activities intensify the factors responsible for erosion and the erosion process is accelerated.

The 'erosion' word was derived from Latin word 'erode' which means to eat away or to excavate. About 111.7 m ha lands in India are degraded due to soil erosion and desertification, 15.5 m ha due to salinity and water logging and 3.2 m ha by nutrients depletion (Lal, 2004). Some country-wise information on soil erosion due the actions of water and wind are given in Table 3.1 and the human activity-induced soil erosion data are given in Table 3.2.

Table 3.1. Land area affected by soil erosion by water and wind in South Asia

Country	Water erosion (Mha)	Wind erosion (Mha)	Total land area (Mha)
Afghanistan	11.2	2.1	65.3
Bangladesh	1.5	0	14.4
Bhutan	0.04	0	4.7
India	32.8	10.8	328.8
Iran	26.4	35.4	165.3
Nepal	1.6	0	14.7
Pakistan	7.2	10.7	79.6
Sri Lanka	1.0	0	6.6
Total	81.74	59.0	677.4

(Source: http://www.wamis.org/agm/pubs/agm8/Paper-15.pdf)

Table 3.2. Global extent of human–induced (Anthropogenic) soil degradation (Lal, 2001)

World Regions	Total Land Area (10 ha)	Human induced soil degradation (10 ha)	Soil erosion (10 ha)	
			Water	Wind
Africa	2966	494	227	186
Asia	4256	748	441	222
South America	1768	243	123	42
Central America	306	63	46	5
North America	1885	95	60	35
Europe	950	219	114	42
Oceania	882	103	83	16
World Total	13013	1965	1094	548

(Source: http://www.wamis.org/agm/pubs/agm8/Paper-15.pdf)

Soil erosion also occurs due to soil compaction, low organic matter, destruction of soil structure, poor internal drainage, salinization, and soil acidity. Although soil erosion is a physical process with considerable variation globally in its severity and frequency, it is also strongly influenced by social, economic, political and institutional factors. The rate of soil loss is normally expressed in units of mass or volume per unit area per unit of time (Young, 1969).

Soil erosion is a three phase phenomena, consisting of the detachment of individual soil particles from the soil mass and their transport by erosive agents such as running water and wind. When sufficient energy is no longer available with the erosive agents to transport the particles, then the third phase called as 'deposition' takes place. Thus, soil erosion may be defined as detachment, transportation and deposition of soil particles from one place to another under the influence of wind, water or gravity forces. The process is illustrated in Figs. 3.2 and 3.3.
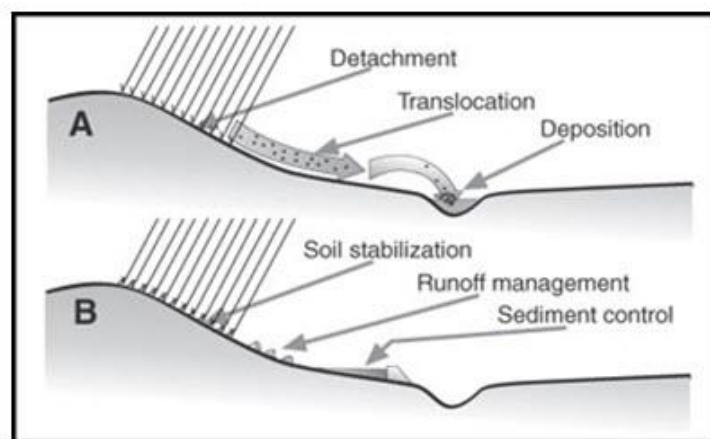
Fig. 3.1. (A) Erosion process, (B) Possible points of intervention.
(Source: http://extension.missouri.edu/p/G1509)

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Fig. 3.2. Effect of topography and climate on water-induced soil erosion. (Source: http://www.britannica.com/EBchecked/media/19386/Effect-of topography-and-climate-on-water-induced-soil-erosion)

Economic & Environmental Effects of Erosion

Erosion has long-term consequences on soil quality and short-term consequences on individual crop. Off-site environmental effects are increasing and becoming more unacceptable to those affected as well as the public at large.

Repeated erosion reduces the fertility of the soil by:

- Removing top soil which is rich in nutrients and organic matter

- Reducing the depth of soil available for rooting and for storing water available for crop growth.

- Reducing infiltration of water into soil and increasing run off.

- Loss of seeds, seedlings, fertilizers and pesticides, and the need to repeat field operations.

- Soil being washed from the roots.

- Young plants being blasted with sand during wind erosion.

3.2 Causes of Soil Erosion

There are two types of causes of soil erosion:

a) Natural Causes:

- Rainfall

- Wind

- Flood

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- Soil Properties

- Lack of vegetative Cover

- Land use and management practices

b) Anthropogenic Causes

- Creating the land surface without vegetation

- Road construction

- Adoption of faulty tillage practices.

- Overgrazing and other forms of biotic pressure on the vegetative cover existing on the land surface

- Absence of vegetative cover

- Improper construction of water channels, roads, rail lines, cattle trails etc.

The major physical agents such as: topography, rainfall, wind, lack of vegetation cover, soil properties, and land use and management practices are the immediate causes of soil erosion. There are some other indirect agents such as: poverty, technical assistance, infrastructure and market development, commodity policy that are also responsible for soil erosion. These are illustrated in Fig. 3.4.
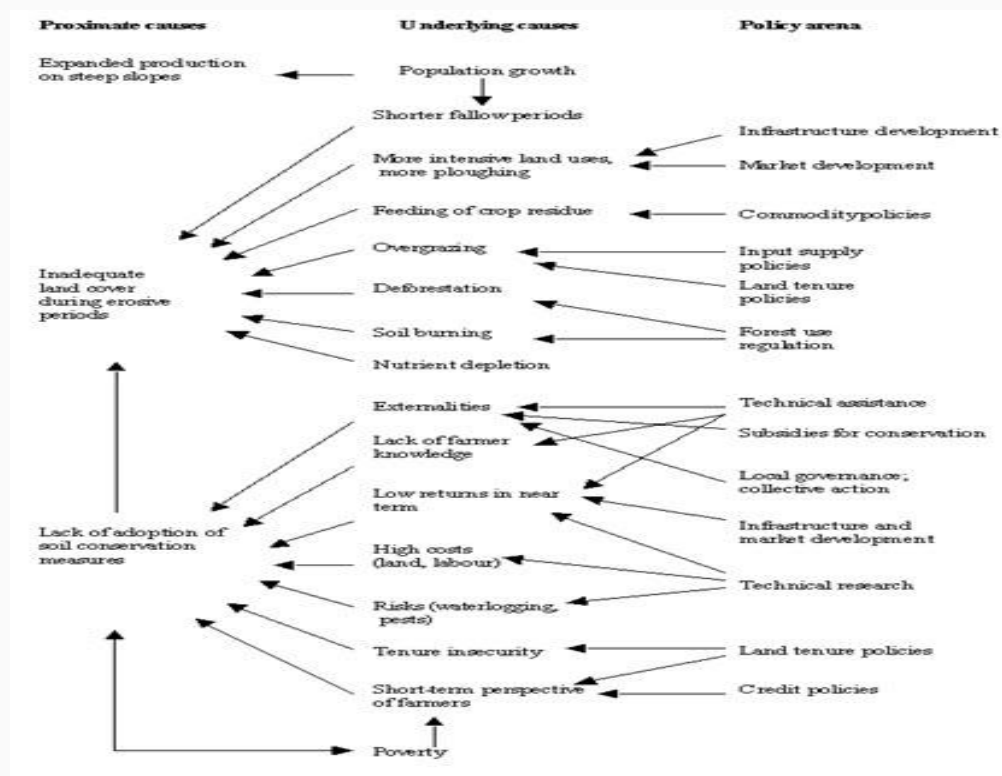
Fig. 3.3. Causes of soil erosion. (Source:
http://ilri.org/InfoServ/Webpub/fulldocs/wp36/land.htm)

3.3 Further Explanation of Erosion Process

Erosion process is classified in to two types:

a) Geologic Erosion

It is the soil erosion that occurs in natural condition without the influence of human being. Geologic erosion is also known as natural or normal erosion. This type of erosion contributes to the formation of soils and their distribution on the earth surface. The geologic erosion is a longtime eroding process. Various topographical features such as existence of stream channels, valleys etc. are the results of geologic erosion.

b) Accelerated Erosion

It is the erosion in excess of geologic erosion. It is activated by natural and human activities which have brought about changes in natural cover and soil conditions. In usual course, the accelerated erosion takes place by the action of water, wind, gravity and glaciers. Water causes the soil erosion through sheet flow, stream flow, wave action and ground-water flow. Similarly wind detaches and transports the soil particle and causes a general mixing of the soil at the surface.

The various forces involved in accelerated erosion are as follows:

1) Destabilizing force of water or wind, which removes and transports the soil particles from one place to another

2) Restoring (retarding) forces which resist the erosion. Normally surface characteristics offer resistance to the erosion.

Water and wind are the primary agents that cause the accelerated erosion.

Accelerated erosion can further be sub-classified as:

1) Water Erosion

The erosive action of water can be separated into two categories:

a) Vertical force of falling water; as raindrop erosion.

b) Horizontal force of flowing water; as sheet, rill and gully erosion.

Both forces detach and move soil particles.

(a) Raindrop Erosion (Splash Erosion)

Splash erosion is the first stage of the erosion process. It occurs when raindrops hit bare soil. The explosive impact breaks up soil aggregates so that individual soil particles are 'splashed' onto the soil surface. The soil may be splashed into the air up to a height of 50 to 75 cm depending upon the size of rain drops. At the same time, the soil particles also move horizontally as much as 1.50 m on level land surface.

(b) Sheet Erosion

Sheet erosion is defined as more or less uniform removal of soil in the form of a thin layer or in "sheet" form by the flowing water from a given width of sloping land. In sheet erosion, two basic erosion processes are involved:

First process involves the detachment of soil particles from the soil surface by falling raindrops and the second process involves the transportation of soil particles by runoff from their original place.

The detachment process is referred to as the raindrop erosion and transportation of detached particles by flowing water is termed as wash erosion.

(c) Rill Erosion

Rill erosion is the detachment and transport of soil by a concentrated flow of water. Rills are small enough to be removed by normal tillage operations. Rill erosion is the predominate form of erosion under most conditions. It is most serious where intense storm occurs on soils with high-runoff-producing characteristics and highly erodible topsoil.

(d) Gully Erosion

Gully erosion is the mature stage of rill erosion. It produces channels larger than rills. These channels carry water during and immediately after rains. The amount of sediment from gully erosion is usually less than that from upland areas, but the inconvenience due to fields being divided by large gullies has been the major problem.

(e) Stream Bank Erosion

Stream bank erosion is defined as the removal of stream bank soil by water either flowing over the sides of the stream or scouring from there. The stream bank erosion caused by wave action is a continuous process in perennial stream. Stream bank erosion is mainly aggravated due to removal of vegetation, over grazing or cultivation on the area near to the stream banks. Stream banks may also collapse when there is a sudden drawdown of the water surface (usually when a flood recedes). During high flow, the stream bank is saturated with water and during drawdown the bank cannot sustain the high water pressure of the saturated soil and they collapse. The various types of erosion, as discussed above, are illustrated in Fig. 3.5.
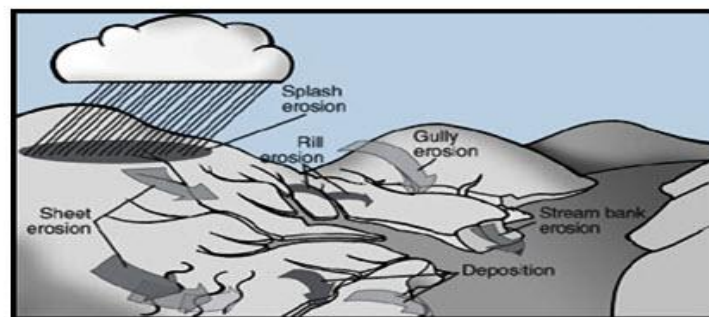
Fig. 3.4. Water erosion. (Source: http://extension.missouri.edu/p/G1509)

2) Wind Erosion

Wind erosion refers to the detachment and transport of soil particles by the forces of moving wind. Wind erosion is the consequence of mismanagement of land resources, such as intensive farming, over grazing, deforestation, etc. These practices destroy the cohesive properties of soil particles and make them susceptible to detachment and movement by wind erosion. Wind erosion is more predominant in arid and semi arid regions because of low annual rainfall. In humid regions, wind erosion occurs only in dry periods of the year, especially when wind blows across cultivated bare fields, having loose, dry and finally divided top soils. Under such condition of land, the high velocity wind produces a large effect on soil erosion. A schematic representation of wind erosion is shown in Fig. 3.6.
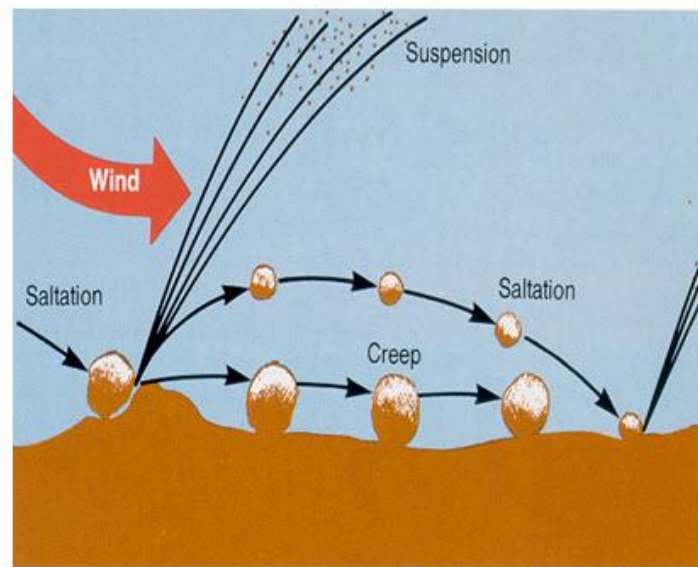
Fig. 3.5. Wind erosion. (Source: http://www.weru.ksu.edu/weps/wepshome.html)

3.4 Other Forms of Erosion

(a) Glacial Erosion

This type of soil erosion is predominant in cold regions, where mean temperature is below 0° C. Most pronounced form of glacial erosion is characterized by furrowing, cutting, and scouring- referred to as execration.

(b) Snow Erosion

Permanent snow cover causes snow erosion. The glacial zones are climatically linked with the zones of snow. In snow erosion, the soil particles are eroded slowly through creeping movement of snow towards leeward slope, where soil is rubbed in downward direction.

(c) Organic Erosion

The soil erosion caused by living organism is called as organic erosion, as illustrated in Fig. 3.7. This type of soil erosion is fairly common in forest. It forms a part of the total destructive geological activities. It is divided into two parts:

Gulley and Ravine Control Structures

a) Phytogenic Erosion- destruction of soil caused by plant root system

b) Zoogenic Erosion- caused by animals, when they move from one place to other place in search of food or excavate for shelters.

**Fig. 3.6. Organic erosion (Phytogenic erosion). (Source:
http://www.onegeology.org/extra/kids/earthprocesses/weathering.html)**

(d) Erosion due to anthropogenic causes

This erosion is associated with the activities of human beings which are responsible to cause soil destruction indirectly. Indirect human activities such as destruction of natural vegetation like deforestation, shifting cultivation, cultivation of crops without soil protection measures, exposing the bare soil, increasing and concentrating runoff and changing the quality of soil are the causes of soil erosion. Deforestation and other anthropogenic activities causing soil erosion are given in Fig. 3.8.
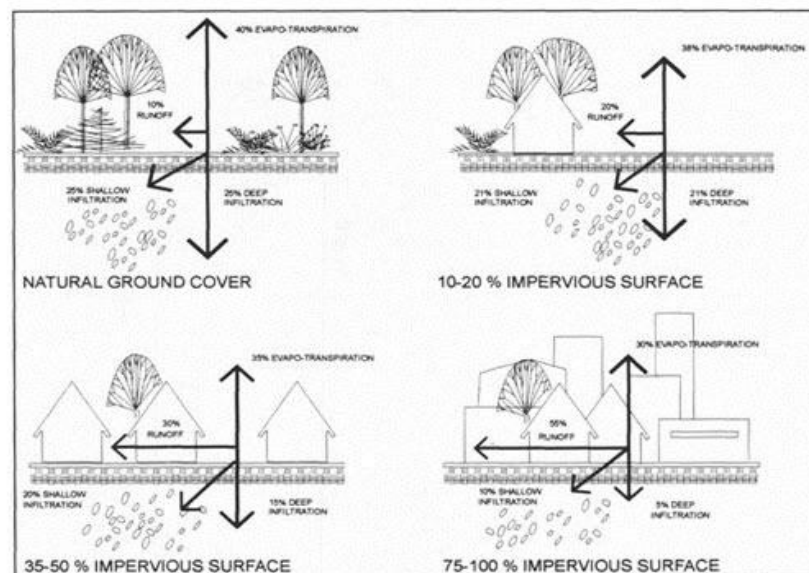
**Fig. 3.7. Anthropogenic erosion. (Source:
http://www.eoearth.org/article/Surface_runoff?topic=58075)**

(e) Underground Erosion

The precipitation causes both surface and underground erosion. The various forms of underground erosion are given below.

i) Intra-soil Erosion

This type of erosion occurs in the soils which comprises of large proportion of gravels or stones that occurs after removal of vegetation. The soil is rapidly washed downward into the coarse Skelton and is partially transported by the underground flow to the lower parts of the slope or in to water courses.

ii) Tunnel Erosion

Tunnel erosion, also known as pipe erosion, is the underground soil erosion and is common in arid and semiarid lands. Tunnel erosion changes the geomorphic and hydrologic characteristics of the affected areas. Runoff in channels, natural cracks, and animal burrows initiates tunnels by infiltrating into and moving thorough dispersible subsoil layers. Presence of water seepage, lateral flow, and interflow is a sign of tunnel erosion. The tunnels or cavities expand to the point where they no longer support the surface weight and collapse, forming potholes and gullies.

(f) River Erosion

This type of erosion occurs particularly in those rivers in which permanent water flow takes place, usually with varying rates. River erosion is likely to be more effective in the water courses of smaller catchment area and those having less favorable conditions for draining the discharge. Fig. 3.9 shows erosion caused by rivers coming down the hill. The kinetic energy causes abrasion and hydraulic action.
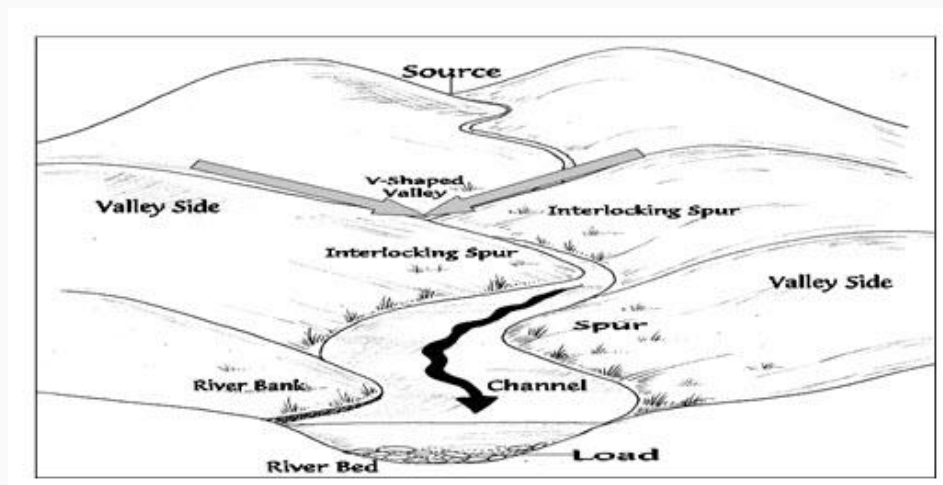
Fig. 3.8. River erosion. (Source: http://igeogers.weebly.com/river-environments.html)

Lesson 4 Factors Influencing Soil Erosion

4.1 Introduction

Soil erosion is mainly caused by the erosive forces of wind and water, besides in varying extents by some other agents, as discussed in Lesson 3. Erosion threatens sustenance of global population with food, nutritional and fiber security, and is closely linked to economy of a country, environmental quality, and human health concerns. Soil erosion by wind and water is the most damaging and widely spread form of land degradation that accounts for 83 percent of the global degraded land. As much as 56 percent of the degraded land is affected by water erosion alone (Oldeman, 1991). Soil erosion affects the water quality; increases flood risk due to elevated river beds on account of deposition of silt carried by flood waters, as well as reduction in general health and productivity of the soil. Erosion results in the reduction of land productivity, reduction in the efficiency of plant nutrient use, damage to seedlings, decrease in plant rooting depth, reduction in the soil's water-holding capacity, decrease in its permeability, and increase in infiltration rate. The threat that land degradation poses to food security of the continuously growing population is especially worrisome for developing countries. The impact of climate change is expected to further aggravate land degradation in the arid and semi-arid regions of the world. At present, about 20 million km² worldwide are affected by reduced productivity due to land degradation. Twenty one per cent of the arable area shows signs of strong and extreme degradation. These are irreversibly destroyed (FAO, UNEP 1992). A schematic diagram Fig. 4.1 shows the different factors that affect the soil erosion in hilly region.
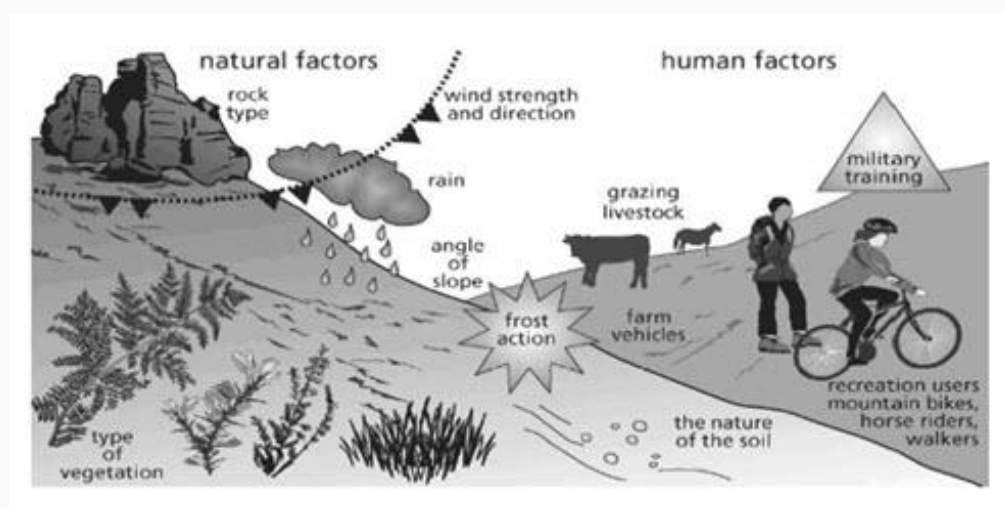
Fig. 4.1. Factors affecting erosion. (Source: http://www.dartmoor-npa.gov.uk/learningabout/lab-printableresources/lab-factsheetshome/lab-erosion)

4.2 Important Factors

The erosion potential of any area is determined by four principal factors: the characteristics of its soil, its vegetative cover, its topography and its climate. Although each of these factors is discussed separately herein, they are inter-related in determining erosion potential.

i) Soil Characteristics

Soil characteristics influencing erosion by rainfall and runoff are those properties which affect the infiltration capacity of soil and those which affect the resistance of the soil to detachment and transport by falling or flowing water. The following four characteristics are important in determining soil erodibility:

- **Soil Texture (particle size and gradation):** soils containing high percentages of fine sands and silt are normally the most erodible. As the clay and organic matter content of these soils increase, the erodibility decreases. Clay acts as a binder for soil particles, thus reducing erodibility.

- **Organic Matter Content:** Organic material is the "glue" that binds the soil particles together and plays an important part in preventing soil erosion. Organic matter is the main source of energy for soil organisms, both plant and animal. It also influences the infiltration capacity of the soil. As shown in Fig. 4.2, lesser soil organic matter causes deterioration of soil structure and soil permeability.

- **Soil Structure:** The way soil particles are held together, affects the soil's friability, the ease with which soil particles are detached by raindrops and runoff, and the resistance of the soil to the growth of roots and shoots.

- **Soil Permeability:** Permeability is the soil's ability to transmit air and water. Soils that are least subject to erosion from rainfall and surface runoff are those with high permeability.

ii) Vegetation Cover

Vegetative cover plays an important role in controlling erosion. It:

- Shields the soil surface from the impact of falling rain

- Holds soil particles in place

- Maintains the soil's capacity to absorb water

- Reduces the velocity of runoff

- Removes subsurface water between rainfalls through the process of evapo-transpiration

iii) Topography

The size, shape and slope characteristics of a watershed influence the amount and rate of runoff. As both slope length and gradient increase, the rate of runoff increases and the potential for erosion is magnified.

iv) Climate

The frequency, intensity and duration of rainfall are fundamental factors in determining the amount of runoff produced in a given area. As both the volume and velocity of runoff increase, the capability of runoff to detach and transport soil particles also increases. Where storms are frequent, intense, or of long duration, erosion risks are high. Seasonal changes in temperature, as well as rainfall influence the erosion risk.
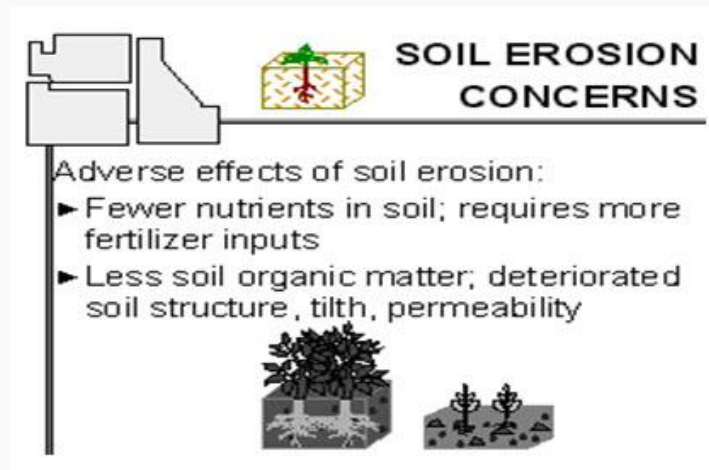
Fig. 4.2. Effect of erosion on organic matter. (Source:
http://www.uiweb.uidaho.edu/wq/wqbr/wqbr22.html)

vi) Deforestation and Burning

The loss of forest cover removes the natural protection of soils against the sun's rays and the direct impact of raindrops. There is a reduction in the infiltration of water in to the soil and a simultaneous increase in surface runoff is resulted and the level of organic material is also reduced. These factors necessitate planting on steep slopes. The natural susceptibility of certain soils to erosion, and the coincidence of land preparation with erosive rainfall, accelerate the erosion process and consequently intensify of land degradation.

The above mentioned activities are a part of "Jhum cultivation" or "shifting cultivation practiced in the hilly regions of northern India, particularly north-eastern Indian states. When burning destroys trees, it also damages the flora and fauna, and affects water availability, for example springs. The problem is no less serious when farmers burn crop residues. It is through crop residue that nutrient recycling occurs in nature. The residues accumulate on the soil surface and release nutrients, which are absorbed directly or indirectly being incorporated in the organic matter. With burning, these nutrients are almost completely lost. Another problem caused by burning is the elimination of the supply of fresh organic matter to the soil.

4.3 Scale of Erosion

It measures the extent of erosion. According to scale of erosion, the erosion may be classified as under:

a) Micro Erosion (1mm^2 to 1m^2)

At this scale, erosion is controlled largely by the stability of the soil aggregates. Soil moisture, organic matter content and the activity of soil fauna, particularly earthworms, have major influences. Erosion in small scale, are identified with sheet erosion and small scale rill erosion.

b) Plot-scale (1m^2 to 100m^2)

Erosion at the plot scale is controlled by the processes that generate surface runoff. These include the infiltration characteristics of the soil and changes in the micro-topography of the surface related to crust development and surface roughness. The spatial distribution of crusted and uncrusted areas or vegetated and bare soil areas determines the locations of runoff and the patterns of flow and sediment movement over the soil surface.

c) Field scale (100m^2 to 10,000m^2)

There is usually a reasonably well defined spatial pattern of runoff pathways in locations such as swales and valley bottoms, separated by areas of either inter-rill erosion or no erosion. The extent of inter-rill erosion depends on the severity of the rainfall event so that the size of the area contributing runoff is quite dynamic. The direction of runoff pathways is often controlled by tillage.

(d) Catchment scale (>10,000m^2)

Erosion is generally limited to local slope wash, but with higher rainfall, runoff pathways develop over the whole hillside with local discharges into the river; with more extreme events, overland flow and slope wash may be widespread.

4.4 Effect of Erosion

a) Soil Health

Soil health refers to the biological, chemical and physical state of the soil and the maintenance of soil ecosystems. Unlike the impact of accelerated erosion on soil, soil health problems may not be immediately evident, but are no less important.

b) Agricultural Productivity

The loss of topsoil results in the loss of small-seeded pasture plants resulting in lower plant density, whilst loosened soil can result in sandblasting damage from wind erosion in young crops. Soil loss can result in reduction in depth of top soil, decrease in capacity of soil to store water and nutrients and limiting the soil available for root exploration, resulting in reduced root and plant vigour. Deposited soil can bury plants and reduce yields.

c) Downstream Environment

Soil erosion increases with runoff. Management of the soil surface to improve infiltration and soil water storage will improve water availability and crop yields at the same time as reducing erosion. Minimizing soil erosion and runoff has important implications for water quality since runoff usually contains sediment, nutrients, agricultural chemicals or other contaminants. Fig. 4.3 shows that soil erosion due to runoff pollutes surface water and also affects the groundwater as the loss of infiltration.
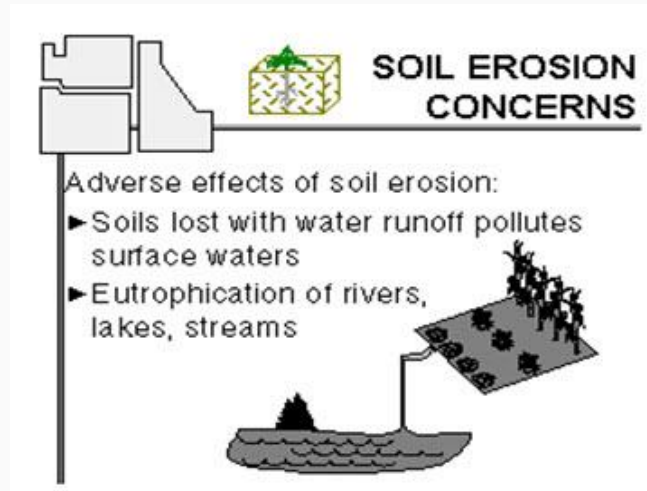
Fig. 4.3. Erosion effect on downstream Environment. (Source: http://www.uiweb.uidaho.edu/wq/wqbr/wqbr22.html)

4.5 Socio Economic Factors

Socioeconomic conditions such as: poverty, population pressure and agricultural intensification are often cited as the most influential factors causing soil erosion (Kirschke et al, 1999). Especially the impact of population growth with equally increasing livestock numbers and higher pressure on resources is likely to be blamed. In areas where the arable land per capita is declining fast due to increasing population density, it is very likely to result in land degradation.

Anthropogenic activities involving deforestation, overgrazing, intensive cultivation, soil management, cultivation on steep slopes, and urbanization accelerate the soil erosion hazard. Land use and management, topography, climate, social and poverty level is linked to soil erosion. The leading three causes of accelerated soil erosion are: deforestation, overgrazing, and mismanagement of cultivated soils. About 35% of soil erosion is attributed to overgrazing, 30% to deforestation, and 28% to excessive cultivation (FAO, 1996).

(i) Poverty and Marginalization

Financial problem abandon farmers to apply new technique in the farm. The part of the population with the lowest financial resources is likely to adapt changes that appear more profitable. Poor farmers are unable to establish conservation practices.

(ii) Population and Land Availability

Rapid growth of population increases the problem of land scarcity, due to degradation or land use changes (e.g. road construction, settlements, large scale plantations etc). This is especially true when the per capita availability of arable land is decreasing. In India, a reduction in per capita availability of cropped area from 0.365 ha (1951) to 0.219 ha (1991) has been observed along with a fast decline in forest area per capita (Kumar, 2004). In some regions of Africa even a direct correlation between human population density and cultivation intensity could be observed.

(iii) Influences on Land Management

The choice of land use and decisions to change it are influenced by the size of the household, age, gender, education, employment, attitudes, values, and personal traits of household members, site-specific conditions—accessibility, regional land-use structure—as well as by transportation cost, profits, parcel size, competition, costs of production, product prices, public and private financial support, land-management practices, land tenure, and ownership. New cash crops that might appear more promising to small-scale farmers are often more soil-degrading and leave the cultivator highly vulnerable to changing market prices due to his lack of means to invest in conservation or fertilizer (Morgan, 2005). Fig. 4.4 shows how the soil conservation impact on recharge.
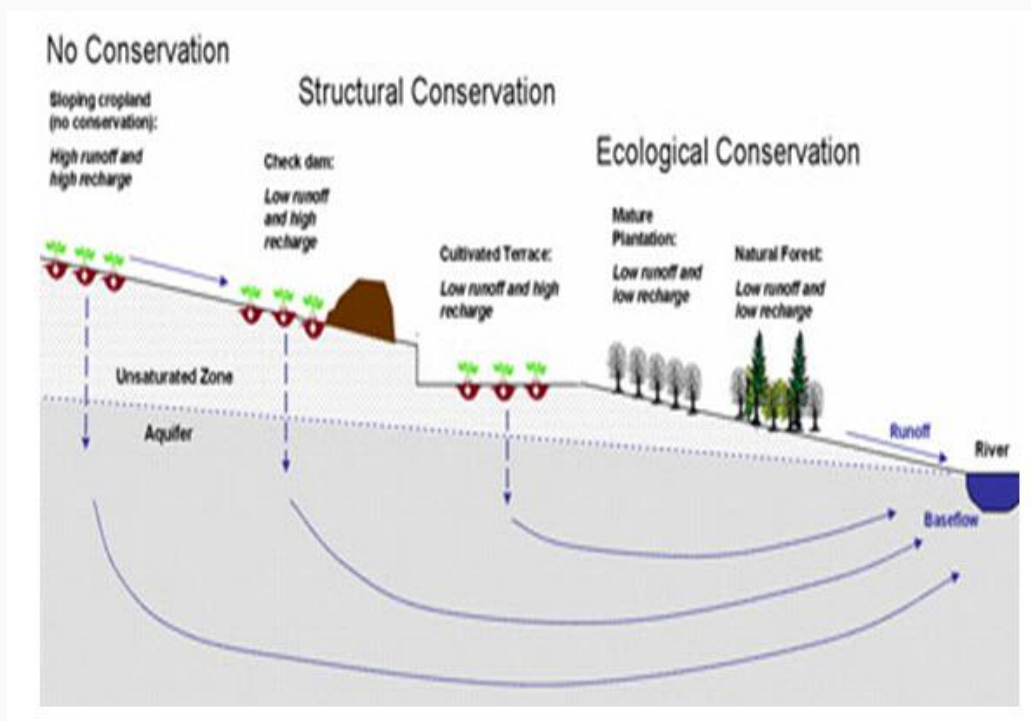
Fig. 4.4. Conceptual overview of soil conservation impact on recharge. (Source: http://www.beg.utexas.edu/cswr/loess.html)

Lesson 5 Mechanism of Erosion

5.1 Introduction

The soil erosion may be defined as detachment, transportation and deposition of soil particles from one place to another place under influence of wind, water and gravity forces (Suresh, R., 2002). Erosion of soil by water is caused by its two forms- liquid as flowing water, and solid as the glaciers. The impact of rainfall causes splash erosion. Runoff water causes scraping and transport of soil particles leading first to sheet erosion, followed by rill erosion and lastly to gully erosion. Water waves cause erosion of bank sides of reservoirs, lakes and oceans. The sub-surface runoff causes soil erosion in the form of pipe erosion. The glacial erosion causes heavy landslides. In India, glacial erosions are mainly confined to Himalayan regions.

5.2 Mechanics of Water Erosion

(1) Raindrop Erosion

Raindrop erosion is soil detachment and transport resulting from the impact of water drops directly on soil particles or on thin water surfaces. The impact of raindrops breaks the soil crust and splashes the soil particles away. Fig. 5.1 shows the raindrop impact. The mass of each raindrop is directly proportional to its kinetic energy. Wischmeier and Smith (1978) gave the following equation for the calculation of K.E.

$$E = 0.119 + 0.0873 \log_{10} I \quad \text{for } I \leq 76$$
$$= 0.283 \quad \text{for } I > 76$$

Where,

E = kinetic energy of raindrop (MJ/ha-mm),

I = rainfall intensity (mm/hr).

Fig. 5.1. Raindrop impact (splash). (Source: http//utexas.edu)

Erosivity of Rainfall

The potential ability of rain to cause erosion is called erosivity of rainfall. Erosivity is expressed by EI_{30} index. Using rainfall and soil loss information from experimental plots Weischmeier et al. (1958) concluded that best estimator of soil loss is a compound parameter, the product of kinetic energy of the storm and the maximum intensity of storm during a continuous period of 30 minute.

The EI_{30} index was developed under American condition and it is reported not to be very accurate under tropical and subtropical conditions. An alternate method was developed to describe the erosivity of rainfall. This is based on concept that low intensities of rainfall cause no erosion and there is a threshold value of intensity at which rain starts to become erosive. Experimental evidence confirmed this concept and it was observed that rainfall intensities less than 25 mm/h have not resulted in significant erosion. The index for erosivity as KE > 25, indicating that the total kinetic energy of the rain falling at intensities greater than 25 mm/h is considered as erosive.

(2) Sheet erosion

Sheet erosion of soil is a conceptual or an idealized form of soil erosion, where the fertile top soil is removed in uniform layers under the action of runoff water or the overland flow. Such type of removal of the top soil in the form of a layer or a sheet is very difficult to visualize. Sheet erosion is affected by flow velocity, flow volume, and physical and chemical properties of soil, etc. In reality, the sheet flow is carried out by very small definable channels called the inter-rills. Raindrop detaches very thin layers of soil particles through splash and the detached particles are then carried through the inter-rills by a very thin layer of the overland flow. The soil erosion by inter-rills is dependent on the erosion that takes place through rills. Fig. 5.2 shows sheet erosion.

Fig. 5.2. Sheet erosion. (Source: http//plantandsoil.unl.edu)

(3) Rill Erosion

Prolonged occurrence of soil erosion through inter-rills, results widening of the inter-rills and formation small channels, called rills. Fig. 5.3 shows the rill erosion.

Fig. 5.3. Rill erosion. (Source: http// milford.nserl.purdue.edu)

These rills carry both the overland flow from the inter-rill areas and the direct flow. In a channeled flow, the depth of flow is more, thus soil erosion is very high from the well-defined channels. Rills carry the sediment brought by the overland flow through its inter-rills, and have a controlling effect on the magnitude of soil erosion.

(4) Gully Erosion

Rills are small in size and can be smoothened by tillage operations. When rills get larger in size and shape due to prolonged occurrence of flow through them and cannot be removed by tillage operations, these are called gullies. Fig. 5.4 shows the gully erosion. Large gullies and their networks are called ravines. Some of the major causes of gully erosion are steepness of land slope, soil texture, rainfall intensity, land mismanagement, biotic interference with natural vegetation, incorrect agricultural practices, etc. Gully erosion gets initiated where the longitudinal profile of an alluvial land becomes too steep due to sediment deposition.

Fig. 5.4. Gully erosion. (Source: http// passel.unl.edu)

Gullies advance due to the removal of soil by flowing water at the base of a steep slope. High intensity of flow or the runoff increases the gully dimensions.

(**5) Stream Channel Erosion**

The tractive force of the flow of water in a drainage channel scours the bed and cuts the soil from its sides. The removal and transportation of soil, in such situations, occurs in three stages: (i) suspension, (ii) saltation, and (iii) surface creep, depending on the physical properties of the soil particles and the flow parameters of the runoff water, namely turbulence, soil particle size, particle distribution, sediment cohesiveness, and specific gravity of the sediment. Poor alignment and the presence of obstructions such as sandbars increase meandering, the major cause of erosion along the bank.

5.3 Factors Inducing Water Erosion

The major variables affecting soil erosion are climate, soil, vegetation, and topography. Of these, vegetation and, to some extent, soil and topography may be controlled. The climatic factors are beyond the power of human being to control.

(i) Climate

Climatic factors affecting erosion are precipitation, temperature, wind, humidity, and solar radiation. Temperature and wind are the most evident through their effects on evaporation and transpiration. However, wind also changes the raindrop velocities and the angle of impact. Humidity and solar radiation are somewhat less directly involved in that they are associated with temperature and the rate of soil water depletion.

(ii) Soil

Physical properties of soil affect the infiltration capacity and the extent to which particles can be detached and transported. In general, soil detachability increases as the size of the soil particles or aggregates increase, and soil transportability increases with a decrease in the particle or aggregate size. That is, clay particles are more difficult to detach than sand, but clay is more easily transported. The properties that influence erosion include soil structure, texture, organic matter, water content, clay mineralogy, and density or compactness, as well as chemical and biological characteristics of the soil.

(iii) Vegetation

The major effect of vegetation in reducing erosion are (1) interception of rainfall by absorbing the energy of raindrops and thus reducing surface sealing and runoff, (2) retardation of erosion by decreased surface velocity, (3) physical restraint of soil movement, (4) improvement of aggregation and porosity of the soil by roots and plant residue, (5) increased biological activity in the soil, and (6) transpiration, which decreases soil water, resulting in increased storage capacity and less runoff.

(iv) Topography

Topographic features that influence erosion are degree of slope, shape and length of slope, and size and shape of the watershed. On steep slopes, runoff water is more erosive, and can more easily transport detached sediment down the slope. On longer slopes, an increased

accumulation of overland flow tends to increase rill erosion. Concave slopes, with lower slopes at the foot of the hill, are less erosive than convex slopes.

5.4 Mechanics of Wind Erosion

Wind erosion is the detachment and transport of soil particles by the forces of moving wind. Wind erosion is caused by mismanagement of land resources, such as intensive farming, over grazing, deforestation, etc. These practices destroy the cohesive properties of soil particles and make them susceptible to wind erosion. Wind erosion process may be divided into three phases: (1) initiation of movement, (2) transportation, and (3) deposition.

(i) Initiation of Movement

Soil movement is initiated as a result of turbulence and velocity of wind. The fluid threshold velocity is defined as the minimum velocity required producing soil movement by direct action of wind, whereas the impact threshold velocity is the minimum velocity required to initiate movement from the impact of soil particles carried in saltation. Except very near the surface and at low velocities (less than about 1m/s), the surface wind is always turbulent. Wind speeds of 5 m/s or less at 0.3 m height are usually considered non-erosive for mineral soils.

(ii) Transportation

The quantity of soil moved is influenced by the particle size, gradation of particles, wind velocity, and distance across the eroding area. Wind, being variable in velocity and direction, produce gusts with eddies and cross currents that lift and transport soils. The quantity of soil moved varies as the cube of the excess wind velocity above the constant threshold velocity, the square root of the particle diameter, and the gradation of soil. The rate of the soil movement increases with the distance from the windward edge of the field or eroded area.

(iii) Deposition

Deposition of sediments occurs when the gravitational force is greater than the forces holding the particles in the air. The process generally occurs when there is a decrease in wind velocity caused by vegetation or other physical barriers, such as ditches, vegetation and snow fences.

5.5 Factors Inducing Wind Erosion

The major factors affecting wind erosion at any location are climate, soil, and vegetation.

(i) Climate

The climatic factors that influence wind erosion are the characteristics of wind itself in addition to the precipitation, humidity and temperature. The climatic factors influence the soil moisture status which in turn influences the susceptibility of the soil for erosion by wind.

(ii) Soil

Textures, structure, density of particles, organic matter content are the soil characteristics that influence erosion by wind. Soil moisture content and surface roughness are the other factors

Gulley and Ravine Control Structures

which have an impotent bearing on wind erosion. Soil moisture content is important as relatively dry soil is subject to wind erosion. Surface crusts when formed have a retarding influence on wind erosion.

(iii) Vegetation

Vegetation influences wind erosion, directly when the area is under vegetation or indirectly by protecting the adjoining areas. Type of vegetation, its height, density and seasonal distribution are the factors influencing wind erosion.

Module 2: Hydrological Parameters Related to Soil Erosion

Lesson 6 Precipitation

6.1 Introduction

The liquid and the solid forms of water falling from the atmosphere onto the earth is called Precipitation. Cooling and condensation of water vapour in the atmosphere gives rise to precipitation. Tiny droplets of water in the atmosphere combine to form larger droplets, which fall under the action of gravity, as illustrated in Fig. 6.1. The common liquid forms of precipitation are rainfall and dew, where as the common solid forms are snowflakes and hails. Hail storms damage orchard and other crops. Falling water drops first cause splash erosion, which later gives rise to sheet, rill and gully erosion due to flowing runoff water. Normally, raindrops range in size from 1 to 7 millimeters in diameter and hit the ground at a speed as high as 30 km/h. The impact of a falling water drop creates a small crater in the soil, ejecting soil particles. These soil particles travel as much as 60 cm vertically and 1.5 m horizontally on a level ground.

Fig. 6.1. Precipitation. (Source: http://www.kidsgeo.com/geography-for-kids/0111-precipitation.php)

Most of the condensed water in clouds does not fall as precipitation because their fall speed is not large enough to overcome updrafts which support the clouds. The water cycle in the environment is shown in Fig. 6.2.
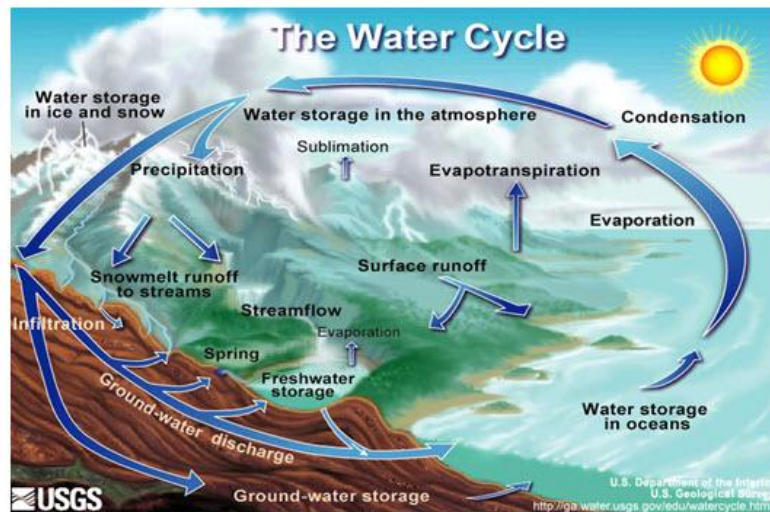
Fig. 6.2. The water cycle. **(Source: http://en.wikipedia.org/wiki/File:Water_cycle.png)**

6.2 Precipitation Process (Hydrological Cycle)

Hydrology is the science, which deals with the occurrence, distribution and disposal of water on the planet earth. It is the science which deals with the various phases of the hydrologic cycle. The **hydrologic cycle, as illustrated in Fig. 6.3,** is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere, and the hydrosphere. Water on our planet can be stored in any one of the following major reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields, and groundwater. Water moves from one reservoir to another by way of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, transpiration, melting, and groundwater flow. The oceans supply most of the evaporated water found in the atmosphere. Out of this evaporated water, only 91% is returned to the ocean basins by way of precipitation. The remaining 9% is transported to areas over landmasses where climatological factors induce the formation of precipitation. The resulting imbalance between rates of evaporation and precipitation over land and ocean is corrected by runoff and groundwater flow to the oceans. The globe has one-third land and two third as water bodies. Water is more or less constantly moving and changing from one state to another (solid, liquid, or vapor/gas) while interacting with the physical processes present in the atmosphere, lithosphere, and biosphere. These changes and movements of water are linked together in the hydrologic cycle. Components of the hydrologic cycle not only include water vapor and clouds in the atmosphere, but also include liquid surface waters (oceans, lakes and streams) on continents as well as groundwater.
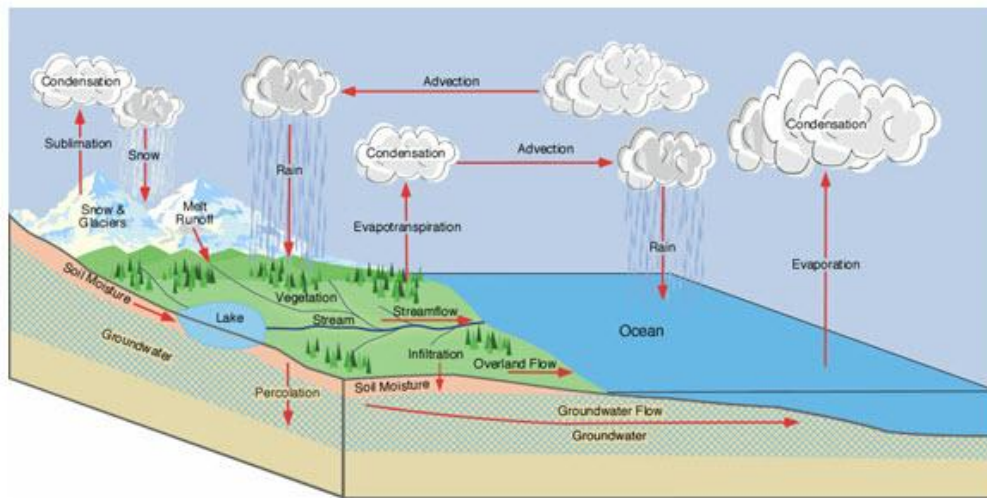
Fig. 6.3. Hydrologic cycle. (Source: http://www.eoearth.org/article/Hydrologic_cycle)

Evaporation takes place from the surfaces of ponds, lakes, reservoirs, ocean surfaces, etc. and transpiration from surface vegetation, as illustrated in Fig. 6.4, from plant leaves of cropped land and forests, etc. These vapours rise up and are condensed at higher altitudes due to cooler temperature to form clouds, resulting in droplet growth and eventually falling onto the earth as precipitation. A part of this precipitation flows over the land as runoff and a part infiltrates into the soil which builds up the groundwater table. The surface runoff joins the streams and rivers, which deliver the water into the seas and the oceans. Rainfall as well as runoff water is also stored in natural depressions and constructed ponds. This water is subjected to evaporation and seepage. Evaporation goes to the atmosphere and seepage joins the groundwater table. The groundwater also moves along the phreatic surface slope. A portion of the surface runoff as well as groundwater flows back to ocean. Again evaporation starts from the surfaces of lakes, reservoirs and ocean, and the cycle repeats. Evaporation, precipitation and runoff are three phases of the hydrologic cycle. The 'runoff phase', which is important to agricultural and civil engineers since they are concerned with the storage of surface runoff in tanks and reservoirs for the purposes of irrigation, municipal water supply, hydroelectric power generation, etc.

Rainfall is the purest form of natural water and is the source of all fresh water of the earth. Water melted from snow is also in a pure form but by the time it becomes available through rivers and streams, it is contaminated to varying extents depending on the terrain it traverses.
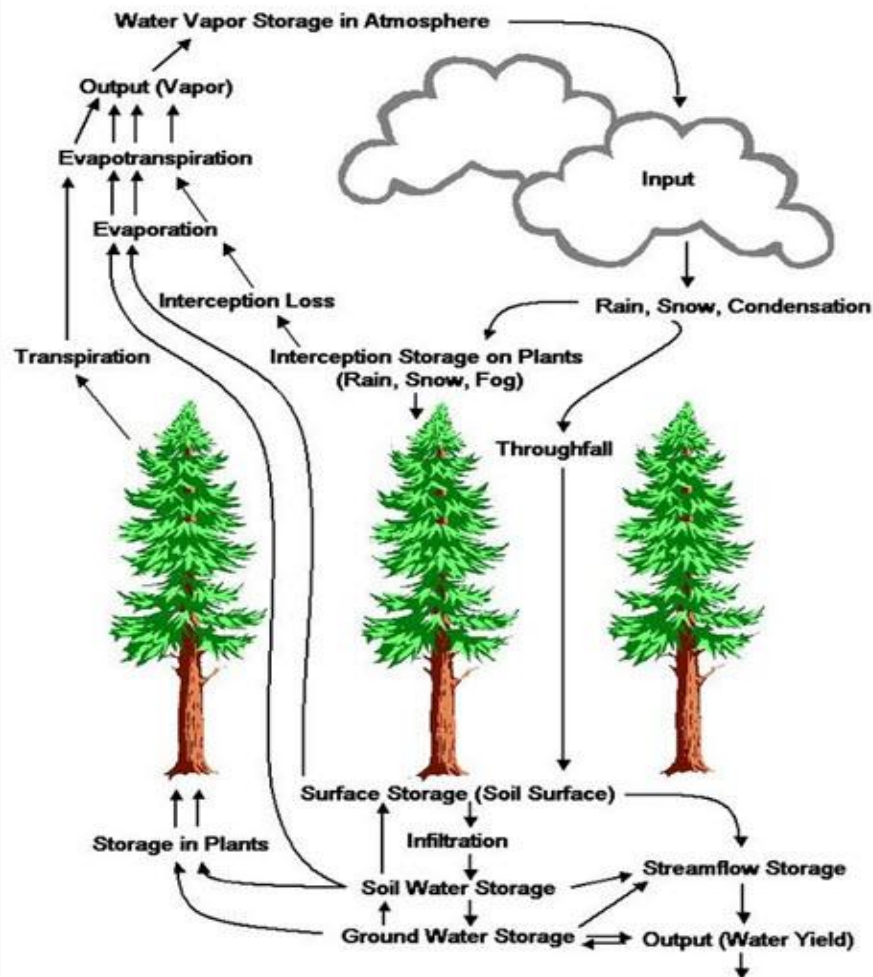
Fig. 6.4. Hydrologic Cycle. (Source: http://www.eoearth.org/article/Hydrologic_cycle)

Global Scale

On an annual basis, approximately 100 cm of water is evaporated from the surface area of oceans. Oceans, which also happen to be the dominant pool in the global water cycle, contain approximately 1,350,000 km^3 of water. Of this, approximately 425,000 km^3 are evaporated to the atmosphere each year, 385,000 km^3 is returned directly to the oceans via precipitation, and 40,000 km^3 is delivered to land by rainfall (net transport to land). At any given time, the atmosphere contains about 13,000 km^3 water, or approximately 0.3 cm of rainfall. It is the large quantities of annual water movement through the atmosphere that results in 111,000 km^3 being precipitated upon land and vegetation and 71,000 km^3, which is either evaporated or transpired (evapotranspiration). Polar and glacial ice reservoirs account for approximately 33,000,000 km^3 of water; water held in soils is equal to approximately 122,000 km^3, and groundwater basins hold approximately 15,300,000 km^3 (http://www.eoearth.org/article/Hydrologic_cycle). Table 6.1 represents the different form of precipitation and their atmospheric condition based on their size and availability.

Table 6.1. Forms of Precipitation

Drizzle	a light steady rain in fine drops (0.5 mm) and intensity <1 mm/h
Rain	the condensed water vapour of the atmosphere falling in drops (>0.5 mm, maximum size—6 mm) from the clouds.
Glaze	freezing of drizzle or rain when they come in contact with cold objects.
Sleet	frozen rain drops while falling through air at subfreezing temperature.
Snow	ice crystals resulting from sublimation (i.e., water vapour condenses to ice)
Snowflakes	ice crystals fused together
Hail	small lumps of ice (>5 mm in diameter) formed by alternate freezing and melting, when they are carried up and down in highly turbulent air currents.
Dew	moisture condensed from the atmosphere in small drops upon cool surfaces.

Classification of Rain based on Intensity

Climatic factors include the amount and intensity of precipitation, the average temperature, as well as the typical temperature range, seasonality, wind speed, and storm frequency. In general, given similar vegetation and ecosystems, areas with high-intensity precipitation, more frequent rainfall, more wind, or more storms are expected to have more erosion. Rainfall intensity is the primary determinant of erosivity, with higher intensity rainfall generally resulting in more erosion. The size and velocity of rain drops is also an important factor. Larger and higher-velocity rain drops have greater kinetic energy, and thus their impact will displace soil particles over larger distances than smaller, slower-moving rain drops.

Rainfall intensity is classified according to the rate of precipitation:

- Light rain — when the precipitation rate is < 2.5 millimeters (0.098 in) per hour

- Moderate rain — when the precipitation rate is between 2.5 millimeters   (0.098 in) - 7.6 millimeters (0.30 in) or 10 millimeters (0.39 in) per hour

- Heavy rain — when the precipitation rate is > 7.6 millimeters (0.30 in) per hour, or between 10 millimeters (0.39 in) and 50 millimeters (2.0 in) per hour

- Violent rain — when the precipitation rate is > 50 millimeters (2.0 in) per hour

Cloud burst

Cloud burst is one of the major natural disasters in the Himalayan region. It is a sudden heavy downpour over a small region and causes devastating flash floods. The cloudbursts

are among the least known mesoscale weather systems, characterized by very high intensity rainfall greater than 100 mm per hour occurring over short duration. Ground monitoring stations are hardly able to capture the storm characteristics due to its highly localized occurrence. Deep cumulus convective clouds cause heavy rainfall over a limited horizontal area, within a short span of time. Such types of extreme rainfall events are most common over the high elevated areas of Northern India during the Southwest monsoon season which causes widespread damage to the property and lives.

6.3 Types of Precipitation

There are different kinds of precipitation:

(1) Orographic

(2) Convectional and

(3) Cyclonic

(1) Orographic Precipitation

Orographic precipitation, as schematic diagram Fig. 6.5, results when warm moist air moving across the ocean is forced to rise over large mountains. As the air rises, it cools. Cold air cannot hold as much moisture as warm air. Clouds form and precipitation occurs on the windward side of the mountain. The air becomes dry and rises over top of the mountain. As the air moves down the mountain, it collects moisture from the ground via evaporation. This side of the mountain is called the leeward side. It receives very little precipitation.

Fig. 6.5. Orographic precipitation. (Source: https://www.oakbay.sd61.bc.ca/staff/cataylor/SS10%20Precipitation%203%20Types%20Diagrams.pdf)
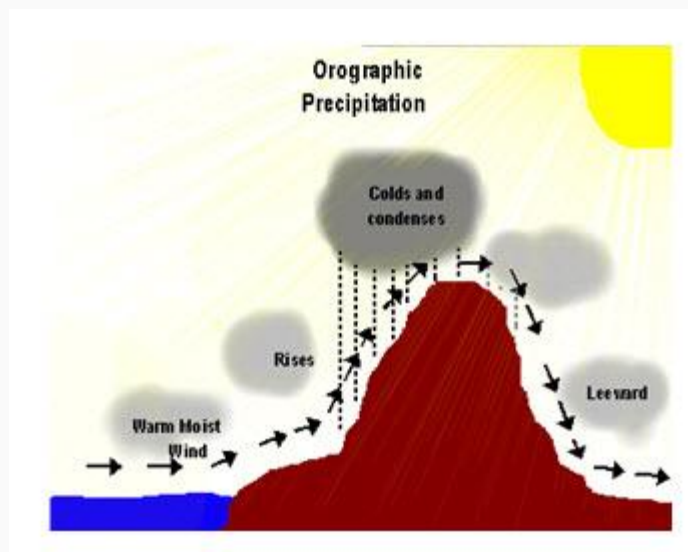
(2) Convectional Precipitation

Convectional precipitation results from the heating of the earth's surface. The warm ground heats the air over it. As the air warms up, the air molecules begin to move further apart. With

increased distance between molecules, the molecules are less densely packed. Thus, the air becomes "lighter" and rises rapidly into the atmosphere. As the air rises, it cools. Water vapour in the air condenses into clouds and precipitation, as shown in schematic diagram Fig. 6.6. This type of precipitation is common in the Prairies and Ontario.

Fig. 6.6. Convectional precipitation. (Source: https://www.oakbay.sd61.bc.ca/staff/cataylor/SS10%20Precipitation %203%20Types%20Diagrams.pdf)
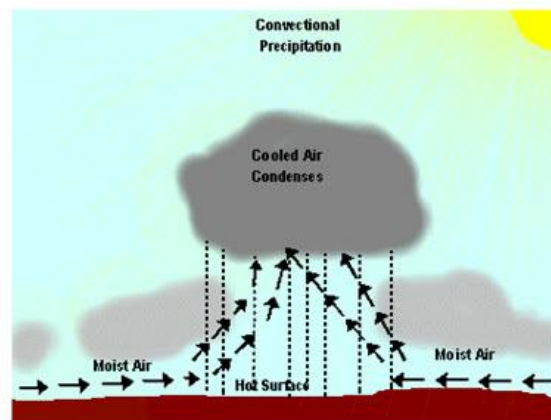
(3) Cyclonic Precipitation

Cyclonic or frontal precipitation, as shown in Fig. 6.7, results when the leading edge of a warm, moist air mass (warm front) meets a cool and dry air mass (cold front). The molecules in the cold air are more tightly packed together (i.e., more dense), and thus, the cold air is heavier than the warm air. The warmer air mass is forced up over the cool air. As it rises, the warm air cools, the water vapour in the air condenses, and clouds and precipitation result. This precipitation is common in Atlantic Canada. This type of system is called Frontal Precipitation because the moisture tends to occur along the front of the air mass. A cyclonic storm is a large, low pressure system that forms when a warm air mass and a cold air mass collide. This collision often occurs under the polar-front jet stream which spreads cold, dry arctic air near warm, moist tropical air. The rotation of the earth causes the air to circulate in a counterclockwise direction around an area of low pressure.

Fig. 6.7. Cyclonic precipitation. (Source:http://www.oakbay.sd61.bc.ca/staff/cataylor/SS10%20Precipitation% 203%20Types%20Diagrams.pdf)
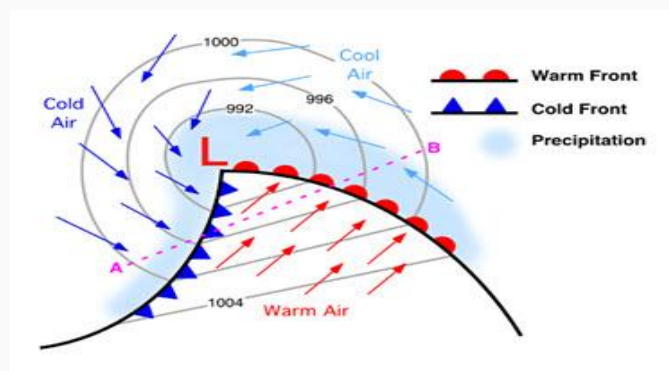
6.4 Characteristics of Precipitation

The Indian subcontinent has two major seasons and two transition periods as follows:

- **South-West Monsoon (June to September):** It is the major rainy season in most parts of India (except the SE part of the peninsula and J&K) accounting for about 75% of the annual rainfall. Monsoon winds advance across the country in two branches viz. The Arabian Sea branch and the Bay of Bengal branch. A low pressure region called monsoon trough is formed between the two branches extending from the Bay of Bengal to Rajasthan. The precipitation pattern over the country is determined by its position.

- **Post Monsoon (North-East Monsoon) (October-November):** As the South West monsoon retreats, low pressure regions form in the Bay of Bengal and a north-easterly flow of air that picks up moisture in the Bay of Bengal is formed. This strikes the east coast of the peninsula causing rain. Also several tropical cyclones form in the Bay of Bengal and the Arabian Sea during this period.

- **Winter (December to February):** Western disturbances cause moderate to heavy rainfall and snowfall in the Himalayas and J&K. Some light rainfall also occurs in northern plains. Low pressure area in Bay of Bengal formed during these months causes 10-12 cm of rainfall in the southern parts of Tamil Nadu.

- **Summer (Pre-monsoon – March to May):** There is very little rainfall in India. Convective cells cause some rain mainly in Kerala, West Bengal and Assam.

6.5 Erosivity and Erodibility

Erosivity is defined as the potential ability of rain to cause the erosion. It is dependent upon the physical characteristics of rainfall, which include raindrop size, drop size distribution, kinetic energy, terminal velocity etc.

Factors Influencing Erosivity

Erosivity is the potential capacity of rain to cause erosion. The various factors, which affect the erosiveness of rain storm, are given below:

i) Rainfall intensity

ii) Drop size distribution

iii) Terminal velocity

iv) Wind velocity

v) Direction of slope

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Erodibility

It is the susceptibility of the soil to get eroded, and is a function of physical characteristics of soil and land management practices. The physical characteristics of soil include the texture, structure, organic matter, land use pattern. On the basis of erodibility, one soil can be compared quantitatively with the other for a given rainfall condition. Small sizes of particles are more erodible than the larger particles; thus the soil composed of high silt content is more erodible.

Lesson 7 Measurement of Precipitation

The term precipitation denotes all forms of water that reach the earth from the atmosphere. The usual forms are rainfall, snow fall, hail, frost and dew. Rainfall is the predominant form of precipitation causing stream flow in a majority of rivers in India. However, many rivers in the northern India acquire their flow from snowmelt also, besides rainfall. The magnitude of precipitation varies with time and space.

7.1 Characteristics of Precipitation in India

India experiences a monsoon climate with two major and two transitional periods of rainfall. These are caused by monsoon winds generated at different times and moving inland from the Arabian Sea in the west and the Bay of Bengal in the east.

(i) South-West Monsoon (June–Sep)

The south-west monsoon is popularly known as monsoon. It is the principal rainy season of India, when 75% of annual rainfall is received over a major portion of the country, except south-eastern part and Jammu & Kashmir. The heavy rainfall areas are:

Assam and north eastern region (200-400 cm)

West coast and Western Ghats (200-300 cm)

West Bengal (120-160 cm)

UP, Haryana and Punjab (100-120 cm)

(ii)Transition I, Post-Monsoon (Oct-Nov)

In this period rainfall occurs in the south eastern part (Tamil Nadu), often accompanied by cyclonic storms coming from over Bay of Bangal, that also affect the neighbouring state of Andhra Pradesh.

(iii)Winter Season (Dec-Feb)

In this period moderate to heavy rainfall and snowfall (25 cm) occurs in the Himalayas and Jammu & Kashmir. The areal spread of winter rain is experienced over many regions in north India but with reduced quantity. The rainfall in India during the non-monsoon seasons (particularly, winter) is also augmented by 'Western Disturbances', which normally refers to the movement of water vapour laden air from the Mediterranean sea towards east. Winter rain is useful for the winter season (Rabi season) crops in meeting a part of their water requirement.

(iv) Transition II, Summer (March-May)

There is very little rainfall in India in this season.

Annual Rainfall

Considerable areal variation exists in the annual rainfall in India with high rainfall of the magnitude 200cm in Assam and north-eastern parts and the Western Ghats, and scanty rainfall in eastern Rajasthan and parts of Gujarat, Maharashtra and Karnataka. The average annual rainfall for the entire country is estimated as 119 cm.

7.2 Raingauge

Raingauge measures the depth and intensity of rainfall.

Types of Raingauge:

(a) Non-recording

(b) Recording

(a) Non-Recording Type Raingauges:

  There are two types of non-recording raingauges

(i) Symon's gauge.

(ii) Standard raingauge

(i) Symon's Gauge

The non-recording type rain gauge commonly used in India is the Symon's gauge.
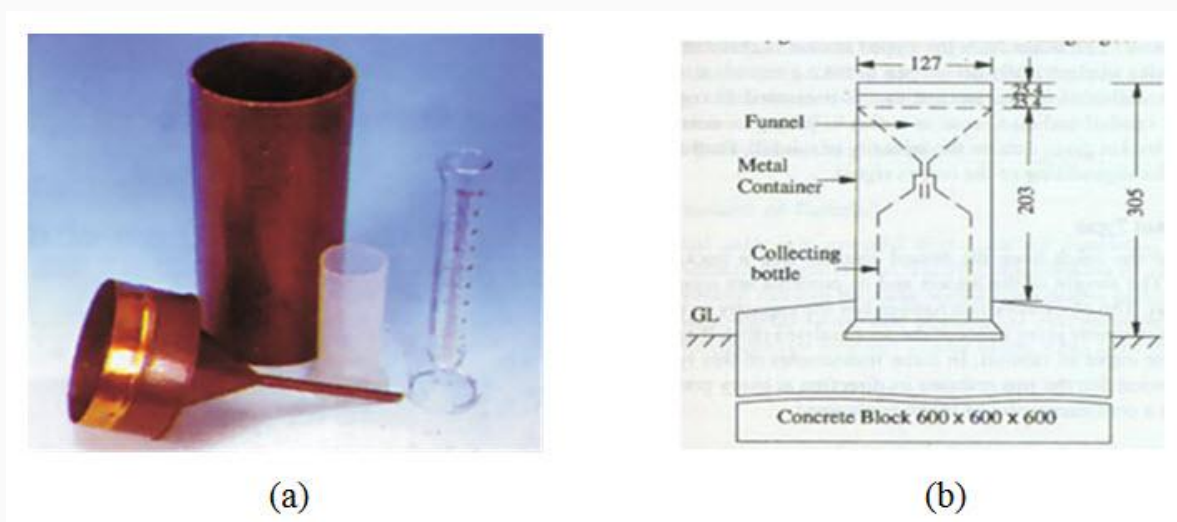
Fig. 7.1. Symon's gauge. (Source: (a): http://www.gb-international.com/product/1052.jpg, (b):http://static7.theconstructor.org/wpcontent/uploads/2010/10/image1.png)

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It consists of a circular collecting area of 127 mm diameter which is connected to a funnel. The rim of the collector is set at a height of 30.5 cm above the ground level. The funnel discharges the rainfall into a receiving vessel. The funnel and receiving vessels are housed in a metallic container. The receiving bottle normally holds a maximum of 10 cm of rain and in case of heavy rainfall the measurement must be done frequently. Last reading must be taken at 8.30 AM and the sum of the previous readings in the past 24 hours entered as the total rainfall of the day.

(ii) Standard Raingauge

This is a basic storage device that measures the cumulative amount of rain. A common type of these gauges is called the 8-inch Standard Rain Gauge (SRG), which has been used by the weather offices of US National Weather Service (NWS) for over 100 years. The standard gauge is simply a large cylinder with a funnel and a plastic measuring tube inside the cylinder.

Fig. 7.2. The national weather service standard rain gauge, SRG. (Source: http://www.srh.noaa.gov/tlh/cpm/srg_page.html)

(b) Recording Raingauges

Recording gauges produce a continuous plot of rainfall against time and provide valuable data of intensity and duration of rainfall for hydrological analysis of storms. The following are some of the commonly used recording raingauges.

(i) Tipping –bucket Type

(ii)Weighing –bucket Type

(iii) Natural syphon or float Type

(iv) Optical raingauges

(i)Tipping–bucket Type

This type of raingauges is adopted by the US Weather Bureau.
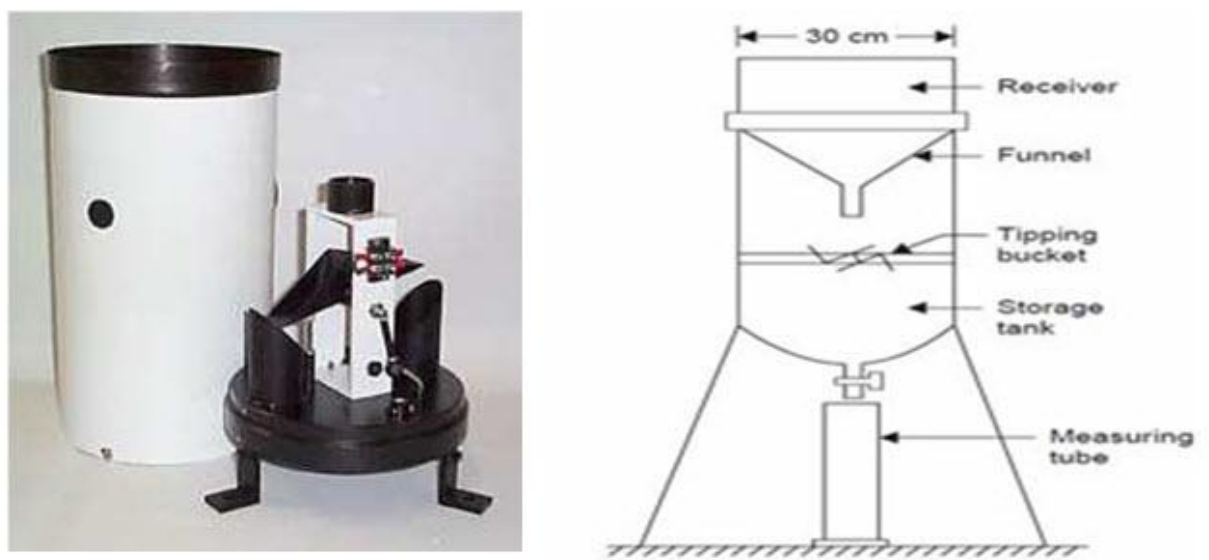
Fig.7.3. Tipping bucket Type raingauge. (Source: (a) NovaLynx corporation, (b) http://www.engineeringsall.com/www.engineeringsall.com/images/featured/Tipping-Bucket-Type-Rain-Gauge.jpg)

The rainfall collected in the funnel falls in one of a pair of small buckets. The buckets are so adjusted that when 0.25 mm of rainfall collects in one bucket, it tips and brings the other one in position. The water from the tipping bucket is collected in a storage can. The tipping bucket consists of a mechanically or electrically driven pen to trace the record on the clockwork driven chart. It gives intensity of rainfall. Tipping buckets tend to underestimate the amount of rainfall, particularly in snowfall and heavy rainfall events. The advantage of the tipping bucket rain gauge is that the character of the rain (light, medium or heavy) may be easily obtained. Rainfall character is decided by the total amount of rain that falls in a set period (usually 1 hour) and by counting the number of 'clicks' in a 10 minute period the observer can decide the character of the rain. Correction algorithms can be applied to the data as an accepted method of correcting the data for high level rainfall intensity amounts.

(ii)Weighing –bucket Type

In this type of raingauge the catch from the funnel empties into a bucket mounted on a weighing scale and the weight of the bucket and its contents are recorded on a clock-driven chart. It gives the plot of accumulated rainfall against the elapsed time that is mass curve of rainfall.

Fig. 7.4. Weighing bucket type raingauge. (Source: www.ametsoc.org)

The advantages of this type of gauge over tipping buckets are that it does not underestimate intense rain, and it can measure other forms of precipitation, including rain, hail and snow. These gauges are, however, more expensive and require more maintenance than tipping bucket gauges.

(iii) Natural syphon or float type

This type of raingauge is adopted as a standard recording type raingauge in India. Here the rainfall collected by a funnel shaped collector is led into a float chamber causing the float to rise. As the float rises, a pen attached to the float records the elevation of the float on a rotating drum driven by clock-work mechanism. A syphon arrangement empties the float chamber when the float has reached a pre-set maximum level. It gives a plot of mass curve of rainfall.

Fig. 7.5. Natural syphon or float type raingauge. (Source: http://upload.wikimedia.org/wikipedia/commons/5/56/Dismantled_Self_Recording_Rain_ Gauge_-_Kolkata_2012-01-23_8704.JPG)

(iv) Optical Raingauges

This is a relatively new technology that is based on measuring rainfall rate as proportional to the disturbance by raindrops to an optical beam between a light source and an optical receiver. This type of rain gauge is relatively expensive and has mainly been used for research purposes.

Fig. 7.6. Optical raingauge. (Source: www.arm.gov)

7.3 Radar Measurement of Rainfall

The meteorological radar is a powerful instrument for measuring the areal extent, location and movement of rain storms. Further, the amount of rainfall over large areas can be determined through the radar with a good degree of accuracy.

Radar measurement of rainfall is based on the principle of reflection of energy. Radio-waves in the "microwave frequencies" are reflected by solid or liquid particles (hydrometeors) in the atmosphere and are determined by electromagnetic energy of radar pulses. The result is displayed on an oscilloscope screen giving the range (distance) and direction (bearing) of the objects being observed. The brightness of the echo image (reflectance) on the screen is related to the number of raindrops, hail or snowflakes falling. Reflectance is used to evaluate the intensity of precipitation as distributed in space and time over the area scanned by the radar.
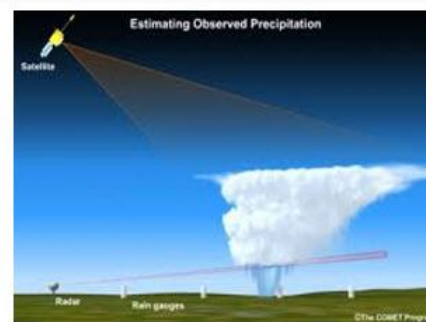
(a)   (b)

**Fig. 7.7. Radar measurement of rainfall. (Source: (a) www2.ucar.edu,
(b) www.meted.ucar.edu)**

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Range of weather radar is approximately 350 km. Indian meteorological department (IMD) is currently operating a network of 40 radars.

7.4 Raingauge Network

Two types of error occur in rainfall measurement, namely random and systemic. Random errors are due to storm characteristics, raingauge density and ability of a raingauge to represent the area that it is supposed to represent. Systematic errors are due to measurement errors, improper siting, poor exposure, change in observer and change in gauge.

In general, the sampling errors of rainfall tend to increase with increasing mean areal rainfall and decrease with increasing network density, duration of rainfall, and areal extent. Accordingly, larger average errors are produced by a particular network for storm rainfall than for monthly, seasonal or annual rainfall. The adequacy of an existing raingauge network of a watershed is assessed statistically.

The optimum number of raingauges corresponding to an assigned percentage of error in estimation of mean areal rainfall can be obtained as

$N = (C_v/\varepsilon)$

Where,

N = optimum number of raingauge.

C_V = coefficient of variation of the rainfall values of the gauges.

ε = assigned percentage of error in estimation of mean areal rainfall   (usually 10 %).

(1) World Meteorological Organization (WMO) Recommended Precipitation Network Density

1. One station per 600 to 900 km^2 - in flat regions of temperate, Mediterranean and tropical zone.

2. One station per 100 to 250 km^2 – in mountainous regions of temperate, Mediterranean and tropical zone.

3. One station per 25 km^2 – in small mountainous land with irregular precipitation.

4. One station per 1500 to 10,000 km^2 – arid and polar zones.

(2) Indian Standard Recommendation

1. One station per 520 km^2 - in plains.

2. One station per 260 - 390 km^2 – in regions of average elevation of 1000 m.

3. One station per 130 km^2 – in predominantly hilly areas with heavy rainfall.

Lesson 8 Analysis of Precipitation Data - I

8.1 Introduction

Statistics is the study of the collection, organization, analysis, interpretation and presentation of data. It deals with all aspects of data, including planning of data collection for experimental design. Statistics also deals with science of understanding uncertainty. Will it rain today? Given that it has not rained for several days, what is the probability that it might rain in the next week? How does a dam affect stream flow? What are the health risks due to drinking contaminated water? These are all questions that statistics might be able to help answer. Probability theory and mathematical statistics are applied to hydrology. Probability theory has been presented in a summarized form here with emphasis on its use in hydrology. The emphasis is on inferential rather than descriptive statistics of classical hydrologic applications.

8.2 Presentation of Rainfall Data

A few commonly used methods of presentations of rainfall data that are useful in interpretation and analysis are given below.

8.2.1 Chronological chart

Presentation of daily, weekly, monthly or annual rainfall data shown either as dots or line joining the dots is known as Chronological chart. Chronological charts may be plotted with a moving mean. A moving mean may be used to damp out or smooth out the oscillations of some of the random variables such as precipitation, stream flow, etc. Fig. 8.1 shows the annual rainfall and average annual rainfall of India in bar chart. As seen from Fig. 8.1, maximum rainfall occurred in 2001 and minimum rainfall occurred in 1986.
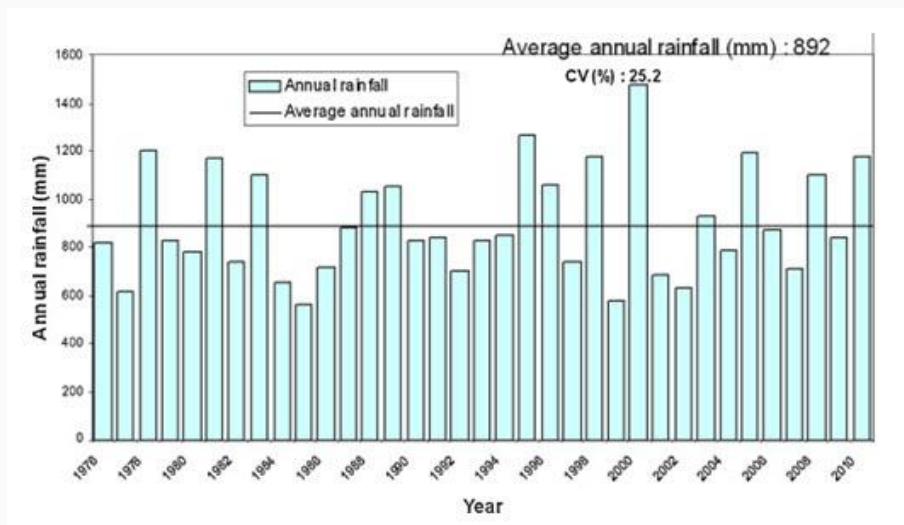
**Fig. 8.1. Annual rainfall of
India. (Source: http://www.sciencedirect.com/science/article/pii/S0378377412003058)**

8.2.2 Mass Curve of Rainfall

The mass curve of rainfall is a plot of the accumulated precipitation against time, plotted in chronological order. Records of float type and weighing bucket type gauges are of this form. A typical mass curve of rainfall at a station during a storm is shown in Fig. 8.2

Fig. 8.2. Mass curve of Rainfall. (Source: http://theconstructor.org/water-resources/analysis-presentation-of-rainfall-data/4493/)
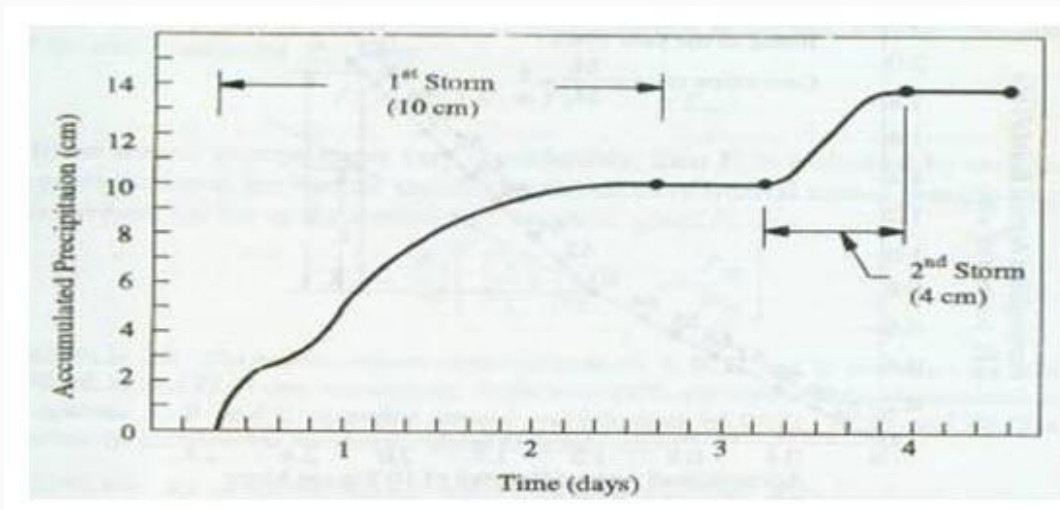
8.2.3 Double Mass Curve of Rainfall

The double mass curve technique, as illustrated in Fig. 8.3, is a reliable procedure for checking the consistency of a precipitation record. The technique compares long term annual or seasonal precipitation of a group of stations being evaluated. Some seasons of the year may have more inconsistencies than others. Therefore, seasonal analysis may provide better results than using total annual values. The accumulated annual or seasonal values for the comparison stations are plotted against the accumulated annual value for the evaluation station.
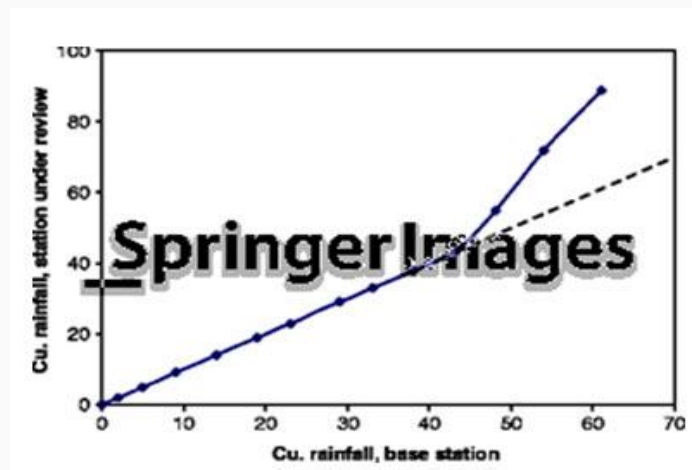
Fig. 8.3. Double Mass Curve of Rainfall.
(Source: http://www.springerimages.com/Images/Environment/1-10.1007_978-1-4419-6335-2_3-4)

8.2.4 Hyetograph

Hyetograph is a plot of the intensity of rainfall against the time interval, as illustrated in Fig. 8.4. The Hyetograph is derived from the mass curve and is usually represented as a bar chart. It is a very convenient way of representing the characterstics of a storm and is particularly important in the development of design storms to predict extreme floods. The area under a hyetograph represents the total precipitation received in the period. The time interval used depends upon the purpose. In urban-drainage problems small durations are used while in flood-flow computations in larger catchments the intervals are of about 6 h.
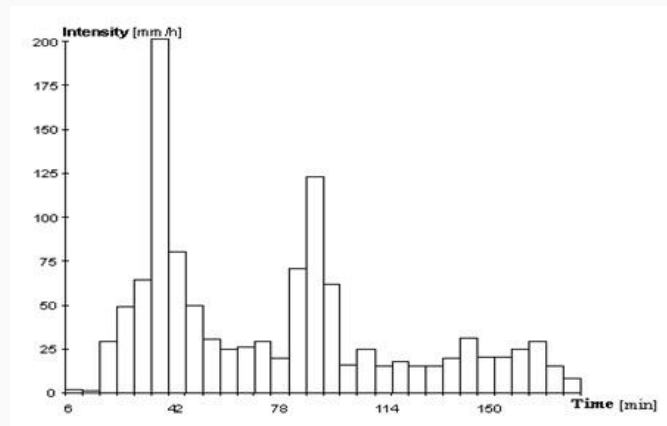
Fig. 8.4. Hyetograph. (Source: http://echo2.epfl.ch/VICAIRE/mod_1b/chapt_2/main.htm)

8.2.5 Hydrograph

The term "Hydrograph" stands for the graphical representation of the instantaneous rate of discharge of a stream plotted with respect to time, as illustrated in Fig. 8.5. This is as a result of the physiographic and hydrometerological effect of the watershed. Hydrographs are graphs which show river discharge over a given period of time and show the response of a drainage basin and its river to a period of rainfall. A storm hydrograph shows how a river's discharge responds following a period of heavy rainfall. On a hydrograph, the flood is shown as a peak above the base (normal) flow of the river.

Fig. 8.5. Hydrograph. (Source: http://web.cortland.edu/barclayj/hydrograph.jpg)
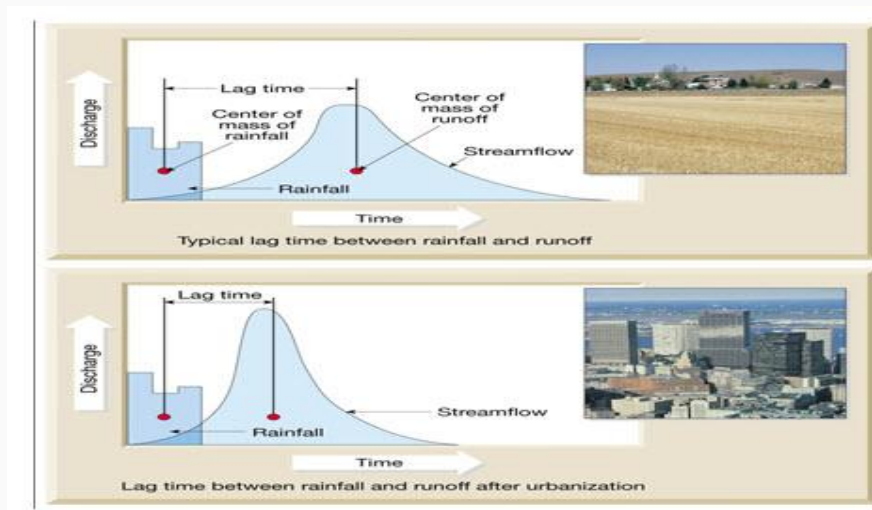
8.2.6 Point Rainfall

The rainfall data measured at a place using a measuring device is known as point (or station) rainfall data. For small areas of less than 50 km², point rainfall may be taken as the average depth over the area. In large areas, there will be a network of rain-gauge stations. Depending upon the need, data can be listed as daily, weekly, monthly, seasonal or annual values for various periods. Graphically these data are represented as plots of magnitude Vs chronological time in the form of a bar diagram. Such a plot, however, is not convenient for subsequent uses. Fig. 8.6 shows the monthly precipitation.
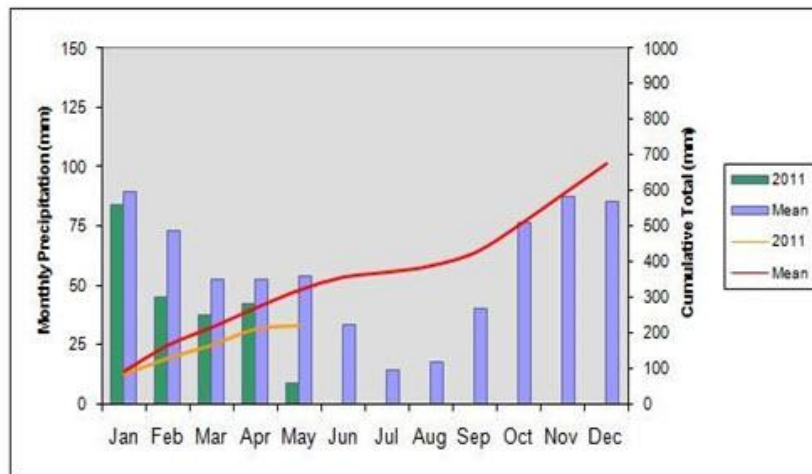
Fig. 8.6. Point Rainfall. (Source: http://malvedos.wordpress.com/2011/07/19/may-2011-douro-insider/)

v **Mean Precipitation Over an Area:** To convert the point rainfall values at various stations in to an average value over a catchment the following three methods are used: i) arithmetical-mean method (ii) Thiessen-polygon method (iii) Isohyetel method.

(i) Arithmetical-Mean Method:

When the rainfall measured at various stations in a catchment show little variation, the average precipitation over the catchment area is taken as the arithmetic mean of the station values. Thus if $P_1, P_2, P_3 \ldots P_n$ are the rainfall values in a given period in N stations within a catchment, then the value of the mean precipitation over the catchment by the arithmitic-mean method is

$$\bar{P} = \frac{(P1 + P2 + P3 + \ldots \ldots + Pn)}{N}$$

(ii) Thiessen Polygon Method

This method attempts to allow for non-uniform distribution of gauges by providing a weighting factor for each gauge, as illustrated in Fig. 8.7. The stations are plotted on a base map and are connected by straight lines. Perpendicular bisectors are drawn to the straight lines, joining adjacent stations to form polygons, known as Thiessen polygons. Each polygon area is assumed to receive uniform rainfall, as recorded by the raingauge station inside it, i.e.,

if P_1, P_2, P_3, ... are the rainfalls at the individual stations, and A_1, A_2, A_3, ... are the areas of the polygons surrounding these stations, (influence areas) respectively, the average depth of rainfall for the entire basin is given by:

$$\bar{P} = \frac{\sum_{i=1}^{M} P_i A_i}{A}$$

where $\Sigma A_i = A$ = total area of the basin.
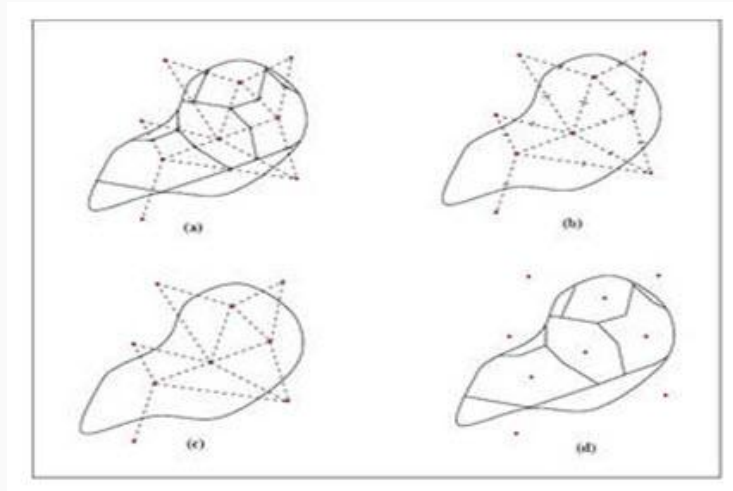
Fig. 8.7. Thiessen polygon method. (Source: http://daad.wb.tu-harburg.de/?id=279)

(iii) The Isohyetal Method

In this method, the point rainfalls are plotted on a suitable base map and the lines of equal rainfall (isohyets) are drawn giving consideration to orographic effects and storm morphology. The average rainfall between the successive isohyets taken as the average of the two isohyetal values are weighted with the area between the isohyets, added up and divided by the total area which gives the average depth of rainfall over the entire basin

$$P_{ave} = \frac{\sum A_{1-2} P_{1-2}}{\sum A_{1-2}}$$

where A_{1-2} = area between the two successive isohyets P_1 and P_2

$$P_{1-2} = \frac{P_1 + P_2}{2}$$

$$\sum A_{1-2} = A = \text{total area of basin}$$

- **Intensity-Duration-Frequency Curve**

The relationship between frequency, intensity and storm duration vary sufficiently from place to place and periodic revisions are desirable in each locality. The relationship between intensity-duration-frequency can be obtained from an analysis of rainfall records obtained at

that location. The intensity of storm decreases with the increase in storm duration. Fig. 8.8 shows the intensity- duration curve over return period.
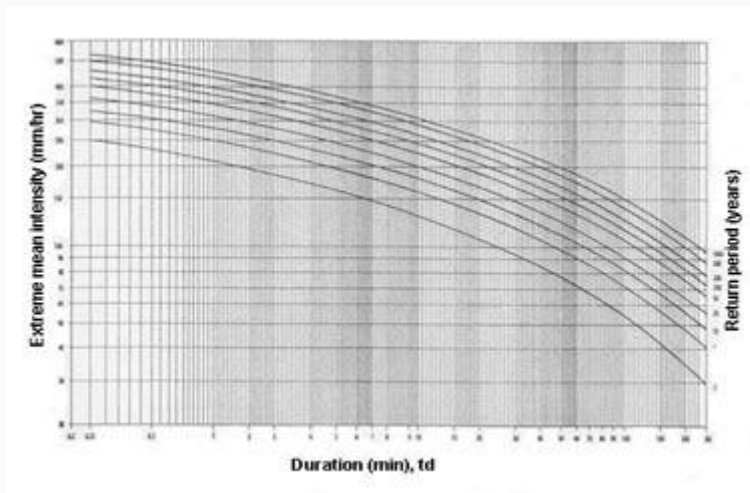
Fig. 8.8. Intensity-duration-frequency curve.
(Source: http://civcal.media.hku.hk/yuenlong/introduction/_idfcurve.htm)

- **Depth-Area-Duration Curve**

A depth-area-duration curve express graphically the relation between a progressively decreasing average depth of rainfall over a progressively increasing area from the centre of the storm outward to its edge for a given duration of rainfall. It can be constructed from any isohyetal map of rainfall for the given duration. Such a curve can be constructed for the duration (usually 6 h, 12 h, 18 h, 24 h, and 36 h) as shown in Fig. 8.9.
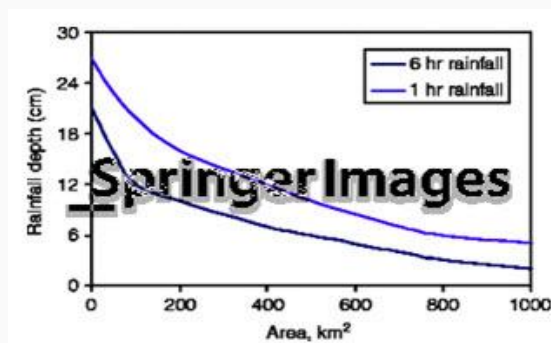
Fig.8.9. Depth-Area-duration curve.
(Source: http://www.springerimages.com/Images/Environment/1-10.1007_978-1-4419-6335-
2_3-1)

8.3 Simple Statistical Analysis

In the study of statistics we are basically concerned with the presentation and interpretation of chance outcomes that occur in a planned or scientific investigation. Hence, the statistician usually deals with either numerical data representing counts or measurements, or perhaps with categorical data that can be classified according to some criterion. We shall refer to any recording of information, whether it is numerical or categorical, as an observation. Statistical methods are those procedures that are used in the collection, presentation, analysis, and

interpretation of data. These methods can be categorized as belonging to one of the two major areas called descriptive statistics and statistical inference.

- **Descriptive Statistics**

Those methods concerned with collecting and describing a set of data so as to yield meaningful information. It provides information only about the collected data and in no way draws inferences or conclusions concerning a larger set of data.

- **Statistical Inference**

Those methods are concerned with the analysis of a subset of data leading to predictions or inferences about the entire set of data.

Fundamental

1. Hydrological Process

Hydrological environment consists of water inputs, environment response and the output. This union of three in one-input, response, output-is described as the basic parts of a hydrologic system, while each of these parts represents a hydrologic process. Natural hydrologic processes are never deterministic but are a combination of various deterministic and stochastic processes.

2. Deterministic Process

These are the processes of hydrology that are the results of physical, chemical and biological deterministic laws. For example, a rating curve of the stage discharge relationship of a river cross section with a fixed bed is a unique function and is thus a deterministic relation giving the same discharge for the same stage at all times.

3. Stochastic Process

These are the processes of hydrology which are governed by the laws of chance such as precipitation, evaporation, and runoff. Stochastic models use random variables to represent processes with uncertainty and generate different results from one set of input data and parameter values when they run under "externally seen" identical conditions. A particular set of inputs will produce an output according to a statistical distribution. This allows some randomness or uncertainty in the possible outcome due to uncertainty in input variables, boundary conditions or model parameters. The application of flood frequency analysis in hydrologic design and operation of water resources systems are good examples of stochastic processes.

Mixed deterministic-stochastic models can also be created by introducing stochastic error models to the deterministic model. For example, stochastic rainfall could be used as an input to a deterministic rainfall-runoff model or a deterministic model may be used to represent a stochastic system. It is important to stress that the term chance, random, probabilistic and stochastic are considered synonyms. They all refer to the phenomena subject to the laws of chance.

Lesson 9 Analysis of Precipitation Data - II

9.1 Depth-Area- Duration Relationship

The rainfall, which is received and measured in a rain gauge is an event at a point in a space (the surface of the earth). But so highly variable the rainfall distribution is, the rainfall may be quite different, say, 1 km away. In fact, it is common to notice that a certain part of a village or a city receiving copious rain, yet another part has not received any. Such differences tend to smoothen out over a larger time interval, say a week or a month. It is also to be noted that the planning and designing of a spillway or a farm pond or a drainage system is to be done in a way that it is able to handle rainfall over a much larger area. The areal distribution characteristics of a storm of given duration is reflected in its depth-area relationship. A few aspects of the inter dependency of depth, area and duration of storms are given below.

For a rainfall of a given duration, the average depth decreases with increase in area, in an exponential manner expressed as:

$$\bar{P} = P_0 \exp(-KA^n) \tag{9.1}$$

Where, = average depth in cm over an area A km², P_0 = highest amount of rainfall in cm during a storm and K and n are constants for a given region.

9.2 Frequency of Point Rainfall

The rainfall occurring at a place is a random hydrologic process and the rainfall data at a place when arranged in chronological order constitute a time series. Thus, daily or weekly total rainfall arranged in a tabular fashion over a month or over a season constitutes the time series of daily or weekly rainfall. One of the commonly used data series is the annual series composed of annual values such as annual total rainfall. If extreme value of a specified event occurring in each year is listed, it also constitutes an annual series. Thus for example, one may list the maximum 24-h rainfall occurring in a year for the duration of 10 years. The probability of occurrence of an event in this series is studied by frequency analysis of this annual data series. The analysis of annual series, even though described with rainfall as a reference is equally applicable to any other random hydrological process.

The probability of occurrence of an event whose magnitude is equal to or in excess of a specified X is denoted by P. The recurrence interval (also known as return period) is defined as:

$$T = \frac{1}{P} \tag{9.2}$$

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This represents the average interval between the occurrence of a rainfall of magnitude equal to or greater than X. Thus if it is stated that the return period of rainfall of 20 cm in 24 h is 10 years at a certain station A, it implies that an average rainfall magnitude equal to or greater than 20 cm in 24 h occurs at least once in 10 years. In a long period of say 100 years, 10 such events can be expected. However, it does not mean that in every 10 years one such event is likely, i.e. periodicity is not implied. The probability of a rainfall of 20 cm in 24 h occurring in any one year at station A is $1/T = 1/10 = 0.1$.

If the probability of an event occurring is P, the probability of the event not occurring in a given year is $q = (1-P)$. The binomial distribution can be used to find the probability of occurrence of the event r times in n successive years. Thus

$$P_{r,n} = {}^nC_r \, P_r \, q^{n-r} = [n! / \{(n-r)! \, r!\} \, P_r \, q^{n-r}] \qquad (9.3)$$

Where, $P_{r,n}$ = Probability of a random hydrologic event (rainfall) of given magnitude and exceedence probability of a random hydrologic event (rainfall) of given magnitude and exceedence probability P occurring r times in n successive years.

9.3 Stochastic Time Series

A time series may be defined as a set of observations arranged chronologically or it is a sequence of observations usually ordered in time but may also be ordered according to some other dimensions.

Time series can be conveniently be divided into two parts:

(1) Continuous Time Series

A continuous time series is a series in which the time variable is continuous. Conversely, even if the time variable itself may be continuous, the phenomenon being described may not necessarily be continuous for a given time, t. Unless analogous computations are carried out, continuous time series must be converted into a discrete form prior to analysis. One of the commonly used examples is the simulation of a chronological record of precipitation and runoff hydrograph.

(2) Discontinuous Time Series

A time series denoted by discrete number of time points, T_i; i = 1, 2....,N is defined as a discontinuous time series, even if the variable itself may be continuous. Thus, rainfall is a continuous variable but often for the convenience in analysis it may be discretised over small time durations.

Time series is used to generate data with the properties of the observed historical records to know the properties of a historical record. The time series is broken into individual components and then analyzed separately to understand the causal mechanism of the different components.

Classification of time series

The time series is classified into two types:

(a) Stationary

In this case, statistical parameters representing the series, such as the mean, standard deviation, etc. do not change from one segment of series to another. Consider for example a 20-year time series of annual maximum 1-day rainfall. This could be divided into two equal parts in several ways such as by making two time series of 10 years each or making two time series of nineteen years each (year 1-19 and year 2-20). Now if the two segments of the maximum 1-day rainfall data exhibit identical mean, identical standard deviation and so on; the 20-year time series will be called stationary. However, this happens rarely with rainfall data of for that matter with most of the hydrologic data. The joint Probability distribution of a set of observations made at times $t_1, t_2, \ldots\ldots\ldots t_N$ in a strictly stationary times series would be identical to that of another N observations made at times $t_1 + k$, $t_2 + k$, $\ldots\ldots\ldots$, $t_N + k$ for all k. The statistical relationship between N observations at origin t is the same as the statistical relationship between N observations at origin t+k. These relationships are measured by correlation between any two time series observation separated by a "lag" of k time units.

(b) Nonstationary

In this, different segments of time series are dissimilar in one or more aspects, because of the effects of seasons and trends on the value of time series. Hydrological time series are invariably non stationary.

Method of Time-Series Analysis

A time series model for the observed data $\{x_t\}$ is a specification of the joint distributions (or possibly only the means and covariances) of a sequence of random

variables $\{X_t\}$ of which $\{x_t\}$ is postulated to be a realization.

Models with Trend and Seasonality

For example, Yue et al. (2002a) investigated the interaction between a linear trend and a lag-one autoregressive [AR(1)] model using Monte Carlo simulation. Simulation analysis indicated that the existence of serial correlation alters the variance of the Mann-Kendall (MK) statistic estimate, and the presence of a trend alters the magnitude of serial correlation. Furthermore, it was found that the commonly used pre-whitening procedure for eliminating the effect of serial correlation on the MK test leads to inaccurate assessments of the significance of a trend. Therefore, it was suggested that firstly trend should be removed prior to ascertaining the magnitude of serial correlation. Both the suggested approach and the existing approach were employed to assess the significance of a trend in the serially correlated annual mean and annual minimum stream flow data of some pristine river basins in Ontario, Canada. It was concluded that the researchers might have incorrectly identified the possibility of significant trends by using the already existing approach.

A General Approach to Time Series Modeling

The following approach can be adopted for the analysis of a given set of observations:

(1) Plot the series and examine the main features of the graph, checking in particular:

Whether there is

(a) A trend,

(b) A seasonal component,

(c) Any apparent sharp changes in behavior,

(d) Any outlying observations.

(2) Identify, quantify and remove the deterministic trend and periodic components, thereby isolating the stationary stochastic component.

(3) Choose a model to fit the residuals, making use of various sample statistics including the sample autocorrelation function.

(4) Forecasting will be achieved by forecasting the residuals and then inverting the

Transformation described above to arrive at forecasts of the original series $\{X_t\}$.

9.4 Serial Correlation

A widely used measure of association between two variables & is the product moment correlation coefficient,

$$\rho = \frac{cov\,(x_t,\ y_t)}{\sigma_{X_t}\sigma_{Y_t}} \qquad\qquad (9.4)$$

Where, the numerator is the covariance of and ; where and may represent the rainfall events of the corresponding period in two consecutive years, and the denominator is the square root of the product of the variances of and .

$$\rho_k = \frac{cov\,[x_t,\ x_{t+k}}{\sigma_{X_t},\ \sigma_{X_{t+k}}} \qquad\qquad (9.5)$$

express the correlation which exists between all pairs of observations, and , within the time series as a function of their spacing, k. The distance k is known as the lag between and . The numerator is referred to as the auto-covariance at lag k. The serial autocorrelation is thus used to account for the effect of serial dependence of series. If the value of time series X , say at time unit t + k is dependent on the value of , then the correlation between the values of and may be taken as the measure of dependence.

The serial coefficient is therefore defined as the correlation coefficient between the members of the series that are k units apart.

If the time series is stationary, then

$$\sigma_{X_t} = \sigma_{X_{t+k}} \qquad (9.6)$$

then the equation becomes:

$$\rho_k = \frac{cov\,[x_t,\ x_{t+k}]}{\sigma_{X_t}^2} \qquad (9.7)$$

9.5 Markov Process

Markov process describes only step by step dependence, called as first - order process, or shows lag-one serial correlation. A Markov process is defined in terms of discrete probabilities.

The probability relationship for a Markov process must provide for the conditional probabilities of the process moving from any state at period t to any subsequent state at period t + 1. Thus

$$P = (X_{t+1=j}\backslash X_{t\,=\,i}) \qquad (9.8)$$

Express the conditional probability of transitioning from state i at time t to state j at time (t + 1). Two conditions must be defined to describe the process completely. One is the initial state, i.e. the value of the variable at the beginning, and the other is the complete matrix of transition probabilities.

A third and resultant property is a statement or matrix of steady-state probabilities which occur in all Markov processes after sufficient transitioning from state to state. The steady-state probabilities are independent of the initial state and transitioning probabilities.

9.6 White Noise Process

A process { (t)} is called a white noise if its values (t$_i$) and (t$_j$) are uncorrelated for every t$_i$ and t$_j$ t$_i$. If the random variables (t$_i$) and (t$_j$) are not only uncorrelated but also independent, then { (t)} is called a strictly white noise process.

For a white noise process (t) with variance the ACVF is given as:

$$R(s) = \begin{cases} \sigma_\varepsilon^2, s = 0 \\ 0, otherwise \end{cases}$$

It will be assumed that the mean of a white noise process is identically zero, unless otherwise stated. White noise processes are important in time series analysis due to their simple structure.

9.7 Moving Average Model MA(p)

By a moving average model of order p, denoted by MA(p), we mean a linear filter of the form

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$X(t) = \varepsilon(t) + b_1 \varepsilon(t-1) + \ldots\ldots\ldots + b_p \varepsilon(t-p)$ \hfill (9.9)

where, (t) is a white noise process. In operator form, this can be written as

$X(t) = P(B) \varepsilon(t)$ \hfill (9.10)

where,

$P(z) = 1 + b_1 z + b_2 z^2 + \ldots\ldots\ldots + b_p z^p$ \hfill (9.11)

and

$BX(t) = X(t-1), \ldots\ldots\ldots, B^i X(t) = X(t-i)$ \hfill (9.12)

MA(p) can be considered as an approximation of a more general form of X(t) in the form

$$X(t) = \sum_{k=0}^{\infty} b_k \, \varepsilon(t-k) \qquad (9.13)$$

by a finite parameter model. Then the spectral density function of X(t) is given by

$$f(w) = \frac{\sigma_\varepsilon^2}{2\pi} \left| 1 + \sum_{k=1}^{p} b_k e^{-iwk} \right|^2 \qquad (9.14)$$

9.8 Autoregressive Moving Average Model ARMA (q, p)

Autoregressive Moving Average (ARMA) models, also known as Box-Jenkins models, are typically used for analyzing and forecasting autocorrelated time series data. The ARMA model is based on two components, an autoregressive (AR) part and a moving average (MA) part, hence known as an ARMA(p,q) model where p is the order of the autoregressive component based on prior observations of y or y values adjusted for systematic variations and q is the order of the white noise moving average component

A stochastic process X(t) is called an ARMA(q, p) model if it satisfies the difference equation 9.14:

$X(t) + a_1 X(t-1) + \ldots\ldots\ldots + a_q X(t-q) = \varepsilon(t) + b_1 \varepsilon(t-1) + \ldots\ldots + b_p \varepsilon(t-p)$
\hfill (9.15)

In operator form this can be given as:

$Q(z)X(t) = P(z) \varepsilon(t)$ \hfill (9.16)

where $Q(z) = 1 + a_1 z + a_2 z^2 + \ldots\ldots\ldots\ldots + a_q z^q$

and $P(z) = 1 + b_1 z + b_2 z^2 + \ldots\ldots\ldots + b_p z^p$

The model possesses a stationary solution only if Q(z) has no zeros inside or on the unit circle.

An ARMA (q; p) model is characterized by a rational transfer function of the form:

$$R(z) = \frac{1 + b_1 z + b_2 z^2 + \ldots\ldots\ldots + b_p z^p}{= 1 + a_1 z + a_2 z^2 + \ldots\ldots\ldots + a_p z^p} = \frac{P(z)}{Q(z)} \qquad (9.17)$$

In engineering literature, MA models are known as all zero models while AR models are known as all-pole models. ARMA models are referred to as pole-zero models.

An ARMA (1;1) process has the general structure:

$$X(t) = a\, X(t-1) + b\, \varepsilon(t-1) + \varepsilon(t) \qquad (9.18)$$

9.9 Autoregressive Integrated Moving Average Model ARIMA (q, r, p)

Box and Jenkins (1970) considered a slightly more general model called ARIMA (q, r, p) in which case Q (B) contains a factor of the form $(1 - B)^r$. Then the transfer function R (z) has a rth order pole at z = 1. Consequently X (t) turns out to be a non stationary process. However, its rth difference X (t) would be stationary.

When r = 0, we get the ARMA (q, p) model. The ARIMA (q, r, p) model can be given in the operator form as:

$$\varnothing(B)(1-B)^r X(t) = \theta(B)(t) \qquad (9.19)$$

This Eqn. 9.17 can be rewritten as:

$$\varnothing(B) Y(t) = \theta(B) \varepsilon(t),\ Y(t) = \Delta^r X(t),\ \Delta = 1 - B \qquad (9.20)$$

Then the reduced process Y(t) Eq. 9.20 will be a stationary ARMA model.

Lesson 10 Runoff

10.1 Introduction

There are a number of definitions of runoff that have been used either explicitly or implicitly in hydrological analyses over the years. Runoff is the part of the rainfall over a catchment area that eventually leaves the catchment as a surface stream flow, whatever is the flow pathway that the water has followed on its way to the stream channel. Thus this definition includes both surface and subsurface runoff pathways.

10.1.1 Runoff Processes in Rural Areas

In arid and semi-arid regions with scarce vegetation and those disturbed by humans (urbanization, etc.), infiltration capacity is a limiting factor and Hortonian overland flow is the dominant process. This also happens when the top soil is frozen. In most humid regions, subsurface flow and saturation overland flow are dominant processes. Where the soils are well-drained, deep and very permeable, the water table is deep and the saturated zone is confined to the valley floor. Saturated overland flow is less important than subsurface flow in this situation. Where the soils are thin, only moderately permeable, and slope is gentle and concave shaped, the water table is shallow and the saturated zone expand readily, the saturated overland flow dominates in this situation.
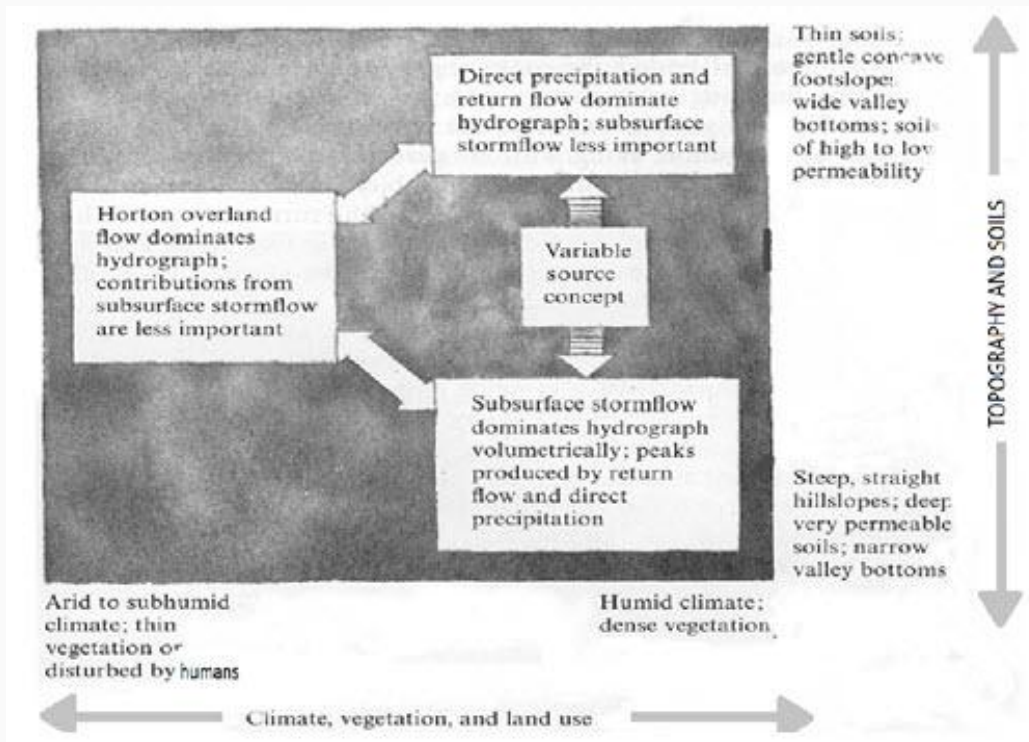
Fig. 10.1. Runoff process for different soils, vegetation and land use.
(Source: http://people.ucalgary.ca/~hayashi/geog515/lectures/515_0607.pdf)

10.1.2 Runoff Processes in Urban Areas

Modification of the land surface during urbanization changes the type and magnitude of runoff processes. Covering parts of the catchment with impervious roofs and concrete lots increases the volume and rate of Horton overland flow. Planners have to design detention ponds to accommodate increased runoff. Gutters and storm sewers convey runoff rapidly to stream channels. The channels are straightened and lined with concrete to increase the efficiency, so that they transmit the flood wave downstream more quickly. A storm hydrograph after urbanization has larger peak flow and shorter lag time than before. The capacity of culverts and bridges are overtaxed and residential areas become flooded during large storms.
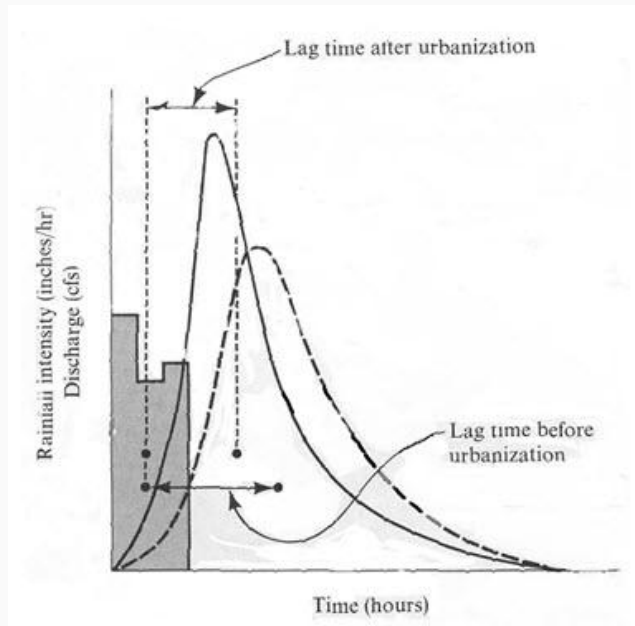
Fig. 10.2. Effects of urbanization on storm hydrographs.
(Source: http://people.ucalgary.ca/~hayashi/geog515/lectures/515_0607.pdf)

10.1.3 Human Activities Affecting Runoff

As population grows and as more development and urbanization occur, more of the natural and pervious landscape is replaced by impervious surfaces, such as roads, houses, parking lots and buildings that reduce infiltration of water into the ground and accelerate runoff to ditches and streams. In addition to increasing imperviousness, deforestation, grading of land surface, construction of drainage networks increase runoff volumes and shorten runoff time into streams from rainfall and snowmelt. As a result, the peak discharge, volume, and frequency of floods increase in streams.

10.1.4 Runoff Cycle

It is that part of hydrological cycle which falls between the phase of precipitation and its subsequent discharge in the stream channels or direct return to the atmosphere through evaporation and evapotranspiration.

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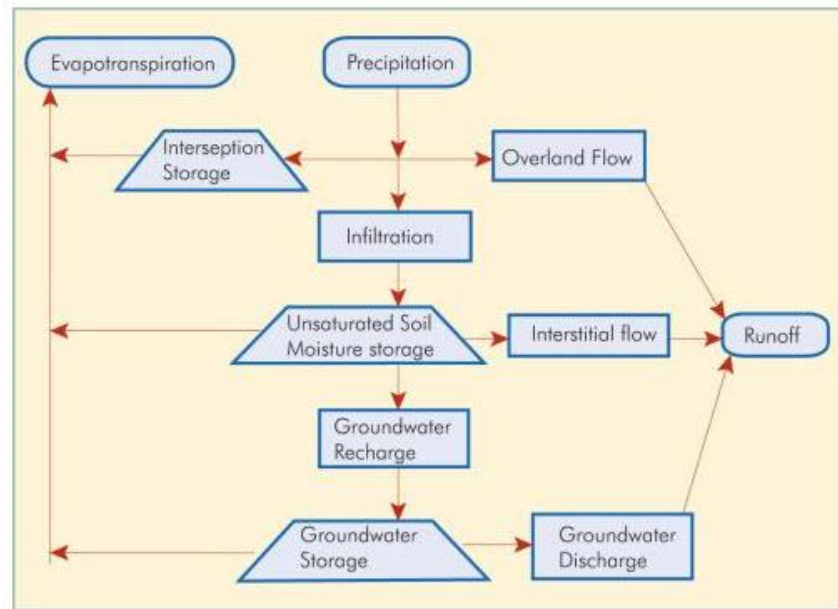
Fig. 10.3. Runoff cycle. (Source: http://texeresilk.com/jquery/14/runoff-cycle)

10.1.5 Conditions Associated With Runoff Cycle

1. As a result of occurrence of a storm rainfall event, from the water that reaches the land surface after satisfying in interception by the vegetation, temporary surface and channel storage build up. The water then starts flowing governed by gravity force when the localized depressions are filled up by water.

2. This process continues simultaneously with infiltration and the channel flow component increases, flowing towards larger streams, tributaries and rivers. The infiltrated water first fills up soil pores in the upper soil layers after which the excess water joins the groundwater table.

3. After this stage and when the rainfall stops, there is no further supply of water and the channel flows start depleting. Meanwhile, the larger surface depressions, ponds, lakes and reservoirs gradually get replenished.

4. The flow that continues thereafter through the rivers flow towards the seas and the oceans.

10.2 Types of Runoff

Based on the time lag between rainfall and runoff, it may be classified in to the following three types:

1. Surface runoff.

2. Sub - surface runoff, and

3. Base flow.

1. Surface Runoff

It is the portion of rainfall which enters the stream immediately after the rainfall when the localized depressions are filled up and the top soil layer is saturated. The short journey of this water flowing over the land as a sheet of water is also called overland flow. This overland flow soon finds paths of lesser resistance such as rills, streams, tributaries, rivers, etc., which all combined is termed as surface runoff.

Fig. 10.3. Surface runoff. (Source: http://milford.nserl.purdue.edu/weppdocs/overview/runoff.html)

2. Sub-surface Runoff

The portion of rainfall, which first infiltrates into the soil and moves laterally without joining the water-table to the streams, rivers or oceans is known as sub- surface runoff. The sub-surface runoff is usually referred to as interflow.
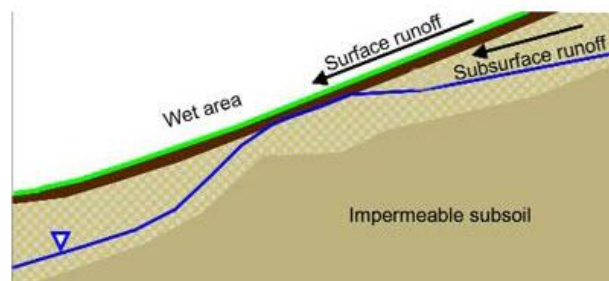
Fig. 10.4. Sub-surface runoff. (Source: http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1294678601507)

3. Base flow

It is the delayed flow, defined as that part of rainfall which after falling on the ground surface infiltrates into the soil and meets the water table and flow towards the streams, rivers, oceans etc. The movement of water in this type of runoff is very slow; that is why it is also referred to as delayed runoff. It takes a long time to join the rivers or oceans. Sometimes base flow is also known as ground water flow. Base flow is not directly contributed by rainfall and

continues much after the rainfall has ceased. In very large catchments and also for snow covered catchments, base flow continues throughout the year giving rise to perennial rivers, as against seasonal rivers, which dry up during the summer. Thus,

Total Runoff = Surface runoff + Base flow (Including sub - surface runoff)
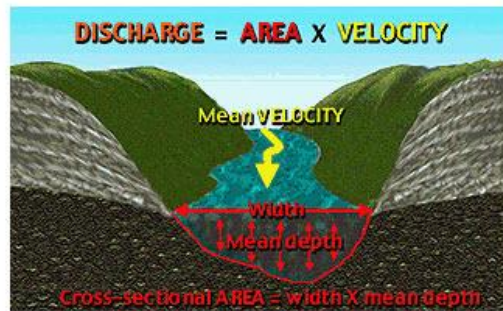
Fig. 10.5. Base flow. (Source: http://www.bigelow.org/virtual/water_sub2.html)

Special Case of Runoff Generation by Snowmelt

Many hydrological regimes, particularly mountain regimes, are dominated by the spring snowmelt component. Snowmelt has particular characteristics in generating the snowmelt hydrograph. It tends to have only low intensities since even after the snowpack is "ripe" and ready for melt, rates of melt are limited on a daily basis by the energy available to supply the latent heat necessary to convert ice and snow to liquid water. Initially, routing through the snowpack may also diffuse the daily melt signal, and there may be some refreezing of water at night. Another interesting feature of the melt process is that it will have a characteristic spatial pattern since, in general, south facing slopes will melt before north facing slopes (in the Northern Hemisphere) and a low elevation snowpack before a high elevation pack. There may also be spatial variations in melt associated with differences in the storage of snow as a result of drifting during the winter period. The response of a catchment during the snowmelt period may depend very much on the state of the soil. If the soil is frozen, then it is likely that infiltration rates may be limited and there is a greater chance of the melt generating a downslope surface runoff through the base of the pack. If the soil is unfrozen, then the low intensity of the melt will usually mean that the bulk of the melt will infiltrate into the soil profile. Depending on the weather conditions prior to a pack being established, it is quite possible that in some years the soil surface remains frozen all winter, while in other years the surface is unfrozen at the start of the melt season.

10.3 Factors Affecting Runoff

Runoff rate and volume from an area are mainly influenced by following four factors:

A. Climatic factors.

B. Physiographical Factors.

C. Metrological factors

D. Storage Characteristics

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(A) Climate Factors

It is associated with characteristics of precipitation which includes:

1. Types of Precipitation

It has great effect on the runoff. Precipitation which occurs in the form of rainfall starts immediately as surface runoff depending upon rainfall intensity while precipitation in the form of snow does not immediately result in surface runoff. It does so only after the snow is melted.

2. Rainfall Intensity

If the rainfall intensity is greater than infiltration rate of soil then runoff starts immediately after rainfall. While in case of low rainfall intensity, runoff starts later. Thus high intensities of rainfall yield higher runoff. Under a monsoon climate, as over India, rainfall intensities are generally higher than the infiltration rate and it is quite common to find runoff occurring even when the lower soil layers remain unsaturated.

3. Duration of Rainfall

It is directly related to the volume of runoff because infiltration rate of soil decreases with duration of rainfall. Therefore medium intensity rainfall even results in considerable amount of runoff if duration is longer.

4. Rainfall Distribution

Runoff from a watershed depends very much on the distribution of rainfall. It is related to the direction of storm movement: from outlet of the catchment upstream and vice-versa. It is also expressed as "distribution coefficient" mean ratio of maximum rainfall at a point to the mean rainfall of watershed. Therefore, near outlet of watershed runoff will be more.

5. Direction of Prevailing Wind

If the direction of prevailing wind is same as drainage system, it results in low peak. A storm moving in the direction of stream slope produces a higher peak in shorter period of time than a storm moving in opposite direction.

6. Other Climate Factor

Other factors such as temperature, wind velocity, relative humidity, annual rainfall etc., affect the water losses from watershed area.

(B) Physiographic Factors

These include both watershed and channel characteristics, which are as follows:

1. Size of Watershed

A large watershed takes longer time for draining the runoff to outlet than a smaller watershed and vice-versa.

2. Shape of Watershed

Runoff is greatly affected by shape of watershed. Shape of watershed is generally expressed by the term "form factor" and "compactness coefficient".

- **Form Factor** is ratio of average width to axial length of watershed

$$F = B/L$$

F, dimensionally equal to $A/\{(L).(L)\} = A/L^2$

- **Compactness Coefficient**

Ratio of perimeter of watershed to circumference of circle whose area is equal to area of watershed

- **Two types of shapes**

a. Fan shape [tends to produce higher runoff very early]

b. Fern shape [tend to produce less runoff].

3. Slope of Watershed

It has complex effect. It controls the time of overland flow and time of concentration of rainfall. For example, a sloppy watershed results in greater runoff due to greater runoff velocity and vice-versa.

4. Orientation of Watershed

This affects the evaporation and transpiration losses from the area. The north or south orientation, affects the time of melting of collected snow.

5. Land Use

Land use and land management practices have great effect on the runoff yield. For example, an area with forest cover or thick layer of mulch of leaves and grasses contribute less runoff because water is absorbed more into soil.

6. Soil moisture

Magnitude of runoff yield depends upon the initial moisture present in soil at the time of rainfall. If the rain occurs after a long dry spell then infiltration rate is more, hence it contributes less runoff.

7. Soil type

Infiltration rate vary with type of soil. So runoff is greatly affected by soil type.

8. Topographic characteristics

It includes those topographic features which affects the runoff. Undulated land has greater runoff than flat land because runoff water gets additional energy [velocity] due to slope and less time to infiltrate.

9. Drainage Density:

It is defined as the ratio of the total channel length [L] in the watershed to total watershed area [A]. Greater drainage density gives more runoff

Drainage density = L/A

(C) Metrological factors

a. Temperature,

b. Humidity

c. Wind velocity

d. Pressure difference

(D) Storage Characteristics

a. Depressions

b. Ponds, lakes and pools.

c. Stream

d. Channels.

e. Check dams in gullies

f. Upstream reservoirs or tanks.

g. Ground water storage in deposits/aquifers

Lesson 11 Computation of Runoff

11.1 Introduction

There are a large number of methods and models in vogue for computation or estimation of runoff from a watershed. Runoff estimation becomes necessary, as the numbers of gauged watersheds are generally small. Particularly the small agricultural watersheds are seldom gauged as a routine. However, runoff and its features must be known for the design of any structure either for storage (e.g. farm ponds) or for safe disposal (e.g. spillways) of the runoff water. Runoff estimation is also required to know the watershed water yield, which is the governing factor for planning irrigation projects, drinking water projects and hydroelectric projects. Runoff is the result of interaction between the rainfall features and the watershed characteristics. Rainfall features are highly variable over space and time and the watershed features are highly variable mainly over space. Such variability precludes the possibility of developing a comprehensive theoretical base for runoff estimation. Hence, most runoff formulas are empirical in nature, arrived at by processing long term monitored data of runoff and the causative rainfall, as well as many of the watershed features. Runoff modeling attempts to take into account a large number of causative factors for estimating runoff. But many times, their complexity and the absence of well and systematically recorded time and space variant data make them difficult to utilize.

Some of the runoff computation/estimations methods are presented in the following pages:

11.2 Rational Method

The Rational Method is most effective in urban areas with drainage areas of less than 80 hectare. The method is typically used to determine the size of storm sewers, channels, and other drainage structures. This method is not recommended for routing storm water through a basin or for developing a runoff hydrograph. However, for the sake of simplicity, the Rational Method is used to determine the size of the detention basin required for construction site.

The rational method is based on a simple formula that relates runoff-producing potential of the watershed, the average intensity of rainfall for a particular length of time (the time of concentration), and the watershed drainage area. The formula is

$Q = 0.28 * C * I * A$

Where Q = design discharge (m³/s), C = runoff coefficient (dimensionless), I = design rainfall intensity (mm/h), and A = watershed drainage area (km²).

Modified Rational Method

The Modified Rational Method (as shown in Fig. 11.1) provides a way to calculate the hydrograph from a catchment based on rational method, C values and the peak intensity.

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There is no "loss method" associated with the modified rational method. The underlying assumption is that the peak intensity is maintained for long enough duration to reach peak flow at the outlet of the catchment. This results in a trapezoidal hydrograph as shown in Fig. 11.1.

In the modified version of the rational formula, a storage coefficient, C_s, is included. In the original formula the recession time was assumed to be equal to the time of rise. The modified rational method is then described by the formula:
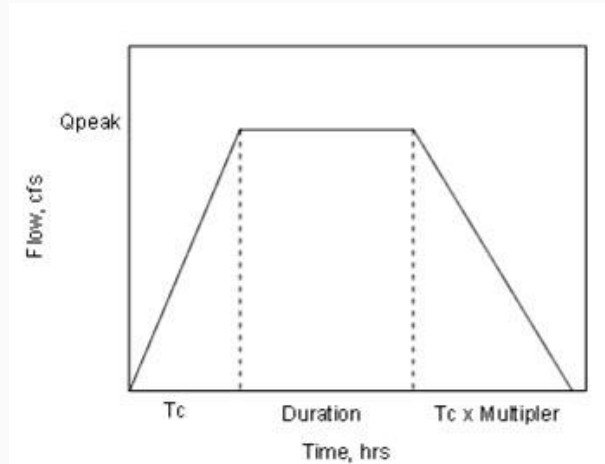
Fig. 11.1. Trapezoidal hydrograph.
(Source: http://docs.bentley.com/en/HMCivilStorm/Help-15-120.html)

$Q_p = 0.28*C_s*C*I*A$

Where C_s is storage coefficient; C, A, I, are same as that of Rational Method.

In the modified version of the Rational Formula, a storage coefficient (C_s) is included to account for a recession time larger than the time the hydrograph takes to rise.

11.3 Kinematic Wave Technique

The kinematic wave technique is a simplified version of the dynamic wave technique. The full dynamic wave technique takes into account the entire spectrum of the physical processes, which simulate hydrologic flow along a stream channel. The kinematic wave simplifies these processes by assuming various physical processes as negligible. Dynamic wave models are based on one-dimensional gradually varied unsteady open channel flow. The dynamic wave consists of two partial differential equations (continuity and momentum), otherwise referred to as the Saint-Venant equations. The Saint-Venant equations take into account the physical laws, which govern both conservation of mass (continuity) and conservation of momentum (dynamic). These physical factors consist of local acceleration, convective acceleration, hydrostatic pressure forces, gravitational forces, and frictional forces.

Kinematic wave models are based on the continuity equation and a simplified form of the momentum equation used for the full dynamic wave. The physical factors which govern the kinematic wave are gravitational forces and frictional forces.

11.3.1 Continuity Equation

The continuity equation applies to both dynamic waves and kinematic waves. The equation is based on the principle of the conservation of mass and is written as:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

Where, Q is the discharge ($m^3\,s^{-1}$), A is the cross-sectional area (m^2), q is the lateral inflow per unit length ($m^3\,m^{-1}$), x is the space coordinates (m), and t is the time (seconds).

11.3.2 (a) Momentum Equation (Dynamic Wave Form)

The momentum equation applies to the full dynamic wave. The equation is based on Newton's second law of motion and is written as:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_o - S_f) = 0$$

Where, y is the flow depth, V is the mean velocity, g is the gravitational acceleration, S_o is the bed slope, and S_f is the friction slope.

11.3.2 (b) Momentum Equation (Kinematic Wave Form)

The simplified version of the full dynamic wave equation applies to kinematic waves. This equation is

$S_f = S_o$

Where, S_f is the friction slope and S_o is the bed slope (gravity).

11.4 Neural Network for Runoff Modeling

The Artificial Neural Network (ANN) is an information processing system composed of many nonlinear and densely interconnected processing elements or neurons, which are arranged in groups called layers. The basic structure of an ANN usually consists of three layers: the input layer, where the data are introduced to the network; the hidden layer or layers, where data are processed; and the output layer, where the results of given input are produced. The inter-connection between neurons is accomplished by using known inputs and outputs, and presenting these to the ANN in some ordered manner; this process is called training. The strength of these interconnections is adjusted using an error convergence technique so that a desired output will be produced for a known pattern. The main advantage of the ANN approach over traditional methods is that it does not require information about the complex nature of the underlying process under consideration to be explicitly described in mathematical form. The merits and shortcomings of this methodology have been discussed in a recent review by the ASCE task committee on application of ANNs in hydrology (ASCE, 2000a,b). They have indicated that rainfall-runoff modelling has received maximum attention by ANN modellers. In a preliminary study, Halff et al. (1993) designed a three-layer feed-forward ANN using the rainfall hyetographs as input and

hydrograph as output. This study opened up several possibilities for rainfall-runoff modeling.

The feed-forward multilayer perceptron (MLP) is the most commonly used ANN in hydrological applications. The structure of a three-layer MLP is shown in Fig. 11.2 and its further elaboration in Fig. 11.3. The number of neurons in the input and output layers are defined based on the number of input and output variables of the system under investigation, respectively. However, the number of neurons in the hidden layer(s), in a study, e.g. a single hidden layer with six neurons, is usually defined via a trial-and-error procedure. As seen from the figure, the neurons of each layer are connected to the neurons of the next layer through weights. In order to obtain optimal values of these connection weights, ANNs must be trained. In some cases, a back-propagation algorithm for training the network, in which the inputs are presented to the network and the outputs obtained from the network are compared with the real output values (target values) of the system under investigation in order to compute error and then the computed error is back-propagated through the network and the connection weights are updated. This procedure, called training procedure, continues until an acceptable level of convergence is reached. In many studies, in order to avoid instability, the neural network is trained a number of times, and by averaging the output from all, a final output is obtained.
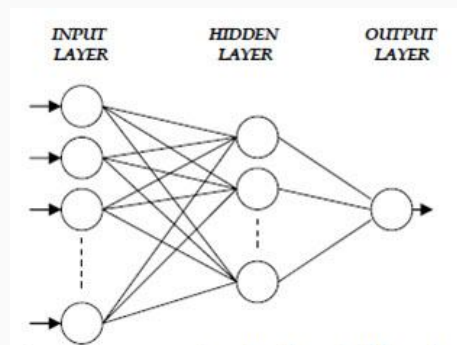
Fig. 11.2. The structure of a 3-layer MLP.
(Source: http://research.guilan.ac.ir/cjes/.papers/958.pdf)
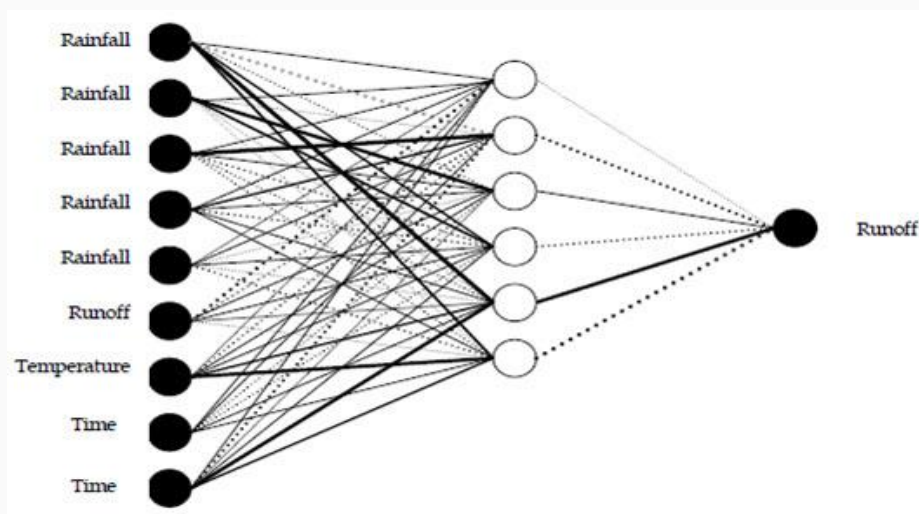
Fig. 11.3. The structure of a 3-layer MLP.
(Source: http://research.guilan.ac.ir/cjes/.papers/958.pdf)

11.5 Storm Water Management Model (SWMM)

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or for long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of sub-catchment areas on which rain falls and runoff is generated. The routing portion of SWMM transports this runoff through a conveyance system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub-catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps.

The model is organized in the form of "blocks". There are four computational blocks and six service blocks in the model (as shown in Fig. 11.4). However, the model is usually run using only the executive block and one or two computational blocks. The runoff and extended transport computational blocks and the executive and graph service blocks are normally used in various studies. The runoff block accepts rainfall and calculates infiltration, surface detention, and overland and channel flow. Rainfall depths from actual storms are used to make the estimates. The SWMM model has two options for calculating infiltration. The first one uses the Green-Ampt equation. The second one uses an integrated form of Horton's equation. Both the Green-Ampt equation and Horton's equation are used in separate simulations. Except for the urban watersheds, infiltration is also routed through subsurface pathways. Subsurface routing is calculated in the runoff block.
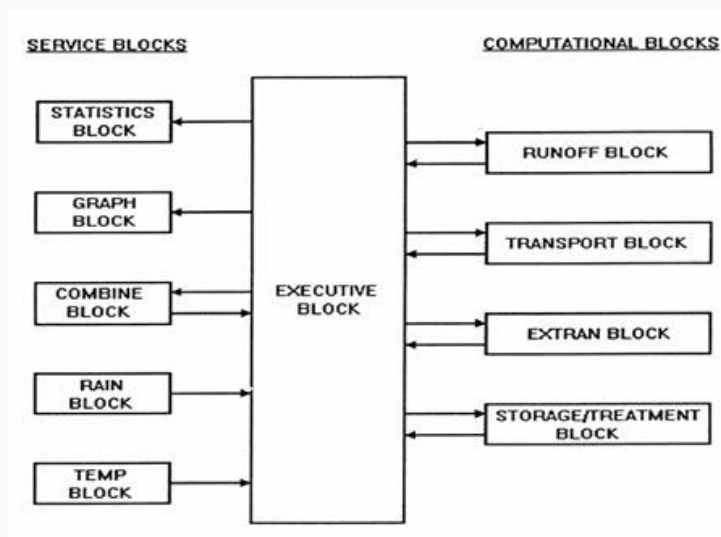
Fig. 11.4. SWMM, the Storm Water Management Model, program configuration. (Source: http://rpitt.eng.ua.edu/Class/Computerapplications/Module9/Module9.htm)

11.6 The TOPMODEL

It is a rainfall-runoff model that bases its distributed predictions on an analysis of catchment topography. The model predicts saturation excess and infiltration excess surface runoff and subsurface storm flow. Since the first article was published on the model in 1979 there have been many different versions. The idea has always been that the model should be simple enough to be modified by the user so that the predictions conform as far as possible to the

user's perceptions of how a catchment behaves. The distributed outputs from the model (as shown in Fig. 11.5) help in such assessments.

The TOPMODEL framework has two components: (1) the storage component, which is represented by three reservoirs and (2) the routing component, which is derived from a distance-area function and two velocities parameters. Its main parameter is the topographic index derived from a digital elevation model. This index represents the propensity of a cell or region to become saturated. The TOPMODEL is considered as a semi-distributed model, as it uses distributed topographic information to determine the topographic index and to distribute saturation deficits throughout the basin, as well. However, its main limitation is the impossibility to use distributed input data, such as rainfall and evapotranspiration
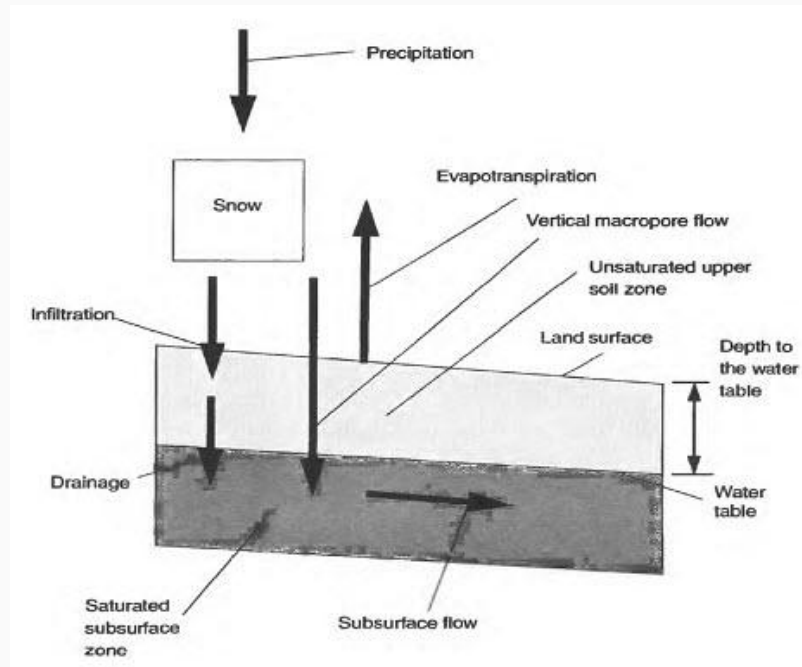
Fig. 11.5. Water fluxes when rainfall or snowmelt occurs on an unsaturated location in the watershed. (Source: http://pubs.usgs.gov/wri/1993/4124/report.pdf)

11.7 Flood Estimation for Gauged Watershed

For a small watershed, the design flood hydrograph can be synthesized from available storm records using rainfall-runoff models, but in case of large watersheds, which provide some hydrological data, a calculated risk can be taken in designing hydraulic structures for a flood lesser than the most severe flood.

A method of dealing with the runoff directly is called the flood frequency method. The method does not provide a hydrograph shape but gives only a peak discharge of known frequency. Frequency studies interpret a past record of events to predict the future probabilities of occurrence. If the runoff data are of sufficient length and reliability, they can yield satisfactory estimates. In most cases, records extend to short length of time and contain relatively few events. Such records when analyzed are likely to lead to inconsistent results as they are not representative of long term trend.

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The value of the annual maximum flood from a given catchment area for large number of successive years constitutes a hydrological data series called the annual series. The data are then arranged in descending order of magnitude and the probability P of each event being equal to or exceeding (plotting position) is calculated by the plotting position formula. If the probability of an event occurring is P, the probability of the event not occurring in a given year is q = (1-P). The binomial distribution can be used to find the probability of occurrence of the event r times in n successive years. Thus

$$P_{r,n} = {}^nC_r P_r q^{n-r} = [n!/\{(n-r)!\, r!\} P_r q^{n-r}]$$

Where, q = 1-P

Two distributions which are widely employed in recent years are: (i) the logarithmic normal and (ii) the extreme value. The methods of analysis based on these distributions can be grouped as: (i) curve fitting methods, graphical or mathematical and (2) methods using Frequency factors comprising: (a) the Gumbel method (b) the lognormal method and (c) other methods such as Foster III, Foster I and Hazen methods.

The curve fitting methods based on frequency factor for hydrologic frequency analysis:

x = + Ks

Where, x = flood magnitude of given return period T, = mean of recorded floods, s = standard deviation of recorded floods, K = frequency factor

(a) Gumbel's Method

Gumbel's distribution is one of the widely used probability distribution functions for extreme values in hydrologic and meteorologic studies for prediction of flood peaks, maximum rainfall, maximum wind speed etc. Gumbel defined a flood as the largest of the 365 daily flows and the annual series of flood flow that constitutes a series of largest value of flows. The probability of occurrence of an event equal to or larger than a value

of $P(X \geq x_0) = 1 - e^{-e^{-y}}$

In which, y is a dimensionless variable given by

$y = \propto(x - a)$

$a = \bar{x} - 0.45005\, \sigma_x$

$\propto = \dfrac{1.2825(x - \bar{x})}{\sigma_x} + 0.577$

Where, = mean and = standard deviation of the variate X. In practices it is the value of X for a given P that is required, $y_p = -\ln[-\ln(1-P)]$

Noting that the return period T = 1/P and designating

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$$y_T = -[\ln. \ln \frac{T}{T-1}]$$

$$y_T = -[0.834 + 2.303 \log. \log \frac{T}{T-1}]$$

Now rearranging, the value of the variate X with a return period T is

$$x_T = \bar{x} + K\sigma_x$$

$$K = \frac{(y_T - 0.577)}{1.2825}$$

Confidence Limit

Since the value of the variate for a given return period, x_T determined by Gumbel's method can have errors due to the limited sample data used; an estimate of the confidence limits of the estimate is desirable. The confidence interval indicates the limit of the calculated value between which the true value can be said to lie with a specific probability based on sampling errors only.

For a confidence probability c, the confidence interval of the variate, x_T is bounded by values x_1 and x_2 given by

$$x_{1/2} = x_T \pm f(c) S_e$$

Where, $f(c)$ = function of the confidence probability c determined by using the table of normal variates.

(b) Log-Pearson Type III Distribution

The statistical distribution most commonly used in hydrology in the United States is the log-Pearson Type III (LP3) because it was recommended by the U.S. Water Resources Council in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). It is widely accepted because it is easy to apply when the parameters are estimated using the method of moments and it usually provides a good fit to measured data.

This method is applied in the following steps:

1. Transformation of the n annual flood magnitudes, Xi, to their logarithmic values, Yi (Yi = log Xi for i=1, 2, ...n).

2. Computation of the mean logarithm, .

3. Computation of the standard deviation of the logarithms, SY.

4. Computation of the coefficient of skewness, Cs.

$$C_s = n\frac{\Sigma(y-\bar{y})^3}{[(n-1)(n-2)S_{y^3}]}$$

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5. Computation of

$$YT = \bar{y} + S_Y K_T$$

Where, K_T is obtained is obtain from table 11.1.

6. Computation of XT = antilog YT.

This method has as a special case the lognormal distribution when CS = 0.

Table 11.3 Skew coefficient for Log Pearson III

Skew coefficient G	Recurrence interval in years and Percent chance ( )					
	2 (50)	5 (20)	10 (10)	25 (4)	50 (2)	100 (1)
3.0	-0.396	0.420	1.180	2.278	3.152	4.051
2.8	-0.384	0.460	1.210	2.275	4.114	3.973
2.6	-0.368	0.499	1.238	2.267	3.071	3.889
2.4	-0.351	0.537	1.262	2.256	3.023	3.800
2.2	-0.330	0.574	1.284	2.240	2.970	3.705
2.0	-0.307	0.609	1.302	2.219	2.912	3.605
1.8	-0.282	0.643	1.318	2.193	2.848	3.499
1.6	-0.254	0.675	1.329	2.163	2.780	3.888
1.4	-0.225	0.705	1.337	2.128	2.706	3.271
1.2	-0.195	0.732	1.340	2.087	2.626	4.149
1.0	-0.164	0.758	1.340	2.043	2.542	3.022
0.8	-0.132	0.780	1.336	1.993	2.453	2.891
0.6	-0.099	0.800	1.328	1.939	2.359	2.755
0.4	-0.066	0.816	1.317	1.880	2.261	2.615
0.2	-0.033	0.830	1.301	1.818	2.159	2.472
0.0	0.0	0.842	1.282	1.751	2.054	2.326
-0.2	0.033	0.850	1.258	1.680	1.945	2.178
-0.4	0.066	0.855	1.231	1.606	1.834	2.029
-0.6	0.099	0.857	1.200	1.528	1.720	1.880
-0.8	0.132	0.856	1.166	1.448	1.606	1.733
-1.0	0.164	0.852	1.128	1.366	1.492	1.588
-1.2	0.195	0.844	1.086	1.282	1.379	1.449
-1.4	0.225	0.832	1.041	1.198	1.270	1.318
-1.6	0.254	0.817	0.994	1.116	1.166	1.197
-1.8	0.282	0.799	0.945	1.035	1.069	1.087
-2.0	0.307	0.777	0.895	0.959	0.980	0.990
-2.2	0.330	0.752	0.844	0.888	0.900	0.905
-2.4	0.351	0.725	0.795	0.823	0.830	0.832
-2.6	0.368	0.696	0.747	0.764	0.768	0.769
-2.8	0.384	0.666	0.702	0.712	0.714	0.714
-3.0	0.396	0.636	0.660	0.666	0.666	0.667

(Source: http://www.nzdl.org/gsdlmod?e=d-00000-00---off-0hdl--00-0----0-10-0---0---0direct-10---4-------0-1l--11-en-50---20-home---00-0-1-00-0-0-11-1-0utfZz-8-10&a=d&cl=CL1.8&d=HASH3b4d99e5f9716ab628b9b2.11.fc)

(c) Log- Normal Method

If the random variable Y = log X is normally distributed, then X is said to be log-normally distributed. Chow(1954) reasoned that this distribution is applicable to hydrologic variables formed as the product of other variables since if $X = X_1 X_2 X_3 X_4 .... X_n$, then Y , which tends to

the normal distribution for large n provided that the Xi are independent and identically distributed.

For the lognormal distribution, the frequency factor is given by chow (1964) as

K_T = [exp ($\sigma_y K_y$ - σ^2_y/2)-1]/[exp(σ^2_y)-1]$^{1/2}$

Where, Y = ln X and K_Y = (YT - μY)/σ_y

The lognormal distribution has the advantages over the normal distribution that it is bounded (X > 0) and that the log transformation tends to reduce the positive skewness commonly found in hydrologic data, since taking logarithms reduces large number proportionately more than it does for small numbers. Some limitations of the lognormal distribution are that it has only two parameters and that it requires the logarithms of the data to be symmetric about their mean.

- **Regional Flood Frequency Analysis**

This technique of frequency analysis to develop a frequency curve at a gauging station on a stream has been dealt with at length in the preceding section. Extension of the result of the frequency analysis of station data to an area requires regional analysis. The regional flood frequency analysis aims at utilizing available records of stream in the topographically similar region on either side of the stream in question so as to reduce sampling errors. The analysis consists of two major parts. The first is the development of the basic dimensionless frequency curve representing the ratio of the flood of any frequency to the mean annual flood. The second part is the development of relation between topographic characteristics of the drainage area and mean annual flood to enable the mean annual flood to be predicted at any point within the region. The combination of the mean annual flood with the basic frequency curve, which is in terms of the mean annual flood, provides a frequency for any location.

- **Procedure**

The following steps can be followed for regions where the Gumbel method produces a flood frequency reasonably accurate at individual stations. The stepwise procedure is given below:

1. All stations in the region with 10 or more year's record are selected.

2. A frequency curve covering the range up to the 100- years flood is obtained by the Gumbel method for each of the individual stations and confidence limits are constructed with 95% reliability on each of these frequency curves.

3. A homogeneity test on the 10-year flood is performed as:

(a) The ratio of the 10-year flood to the mean annual flood is determined from the frequency curve of each station. These ratios are averaged to obtain the mean 10-year ratio for the year.

(b) The return period corresponding to the mean annual flood times the mean 10-year ratio is determined from the frequency curve of each station and plotted against the number of years of record for that station on a test graph. If the points for all of the stations lie between the 95% confidence limits, then they are considered homogenous.

The 95% confidence band, the spread to be expected for the chance variation on the test graph, the upper and lower limits of a 10-year flood for each station are computed corresponding to the 95% confidence band. The test is performed on a 10-year flood as it is the longest recurrence interval for which most records will give dependable estimates.

4. A set of flood ratios (ratio of flood to mean annual flood) is computed for each of the stations satisfying the homogeneity test for different return periods with the help of station frequency curves.

5. For each selected return period, the median of the ratio from all the stations is computed. The resulting medians values give the regional curve. These are plotted on an extreme value probability paper and the best fit line is drawn through them. This line is the required regional frequency curve.

Since the number of stations in the region is generally less than 10 for want of data in developing countries, the mean is a more stable parameter than the median. The CWC recommends the use of the mean instead of the median in the above analysis.

6. To compute confidence band limits for the regional curve, the width of the confidence band at arbitrarily selected return periods is read from each of the individual curves. The widths are then divided by the respective mean annual floods to produce a set of ratios which may be called errors in the individual curves. The errors are combined by computing the root of the sum of their squares and then dividing by the number of stations. The resulting ratio is taken as the error in the regional error estimate, i.e. the width of the confidence band for the regional curve at the selected return period. The procedure is repeated with another return period.

- **Application to Ungagged Basin**

Regional frequency curves have their most useful application in estimating the flood potential of an ungauged basin, since such curves show the ratio of flood to the mean annual flood for the ungauged basin. The mean annual flood is dependent upon many variables, the most important and commonly available being the drainage area. A correlation is usually therefore established graphically by plotting mean annual flood against respective drainage areas of all gauged stations in the region on logarithmic paper and the relation is used to obtain the mean annual flood for the region having the ungauged area. The flood of any given frequency for the ungauged area is then obtained by determining the corresponding flood ratio from the regional-frequency curve for the region of which the ungauged basin is a part and multiplying it by the estimated mean annual flood of the ungauged basin.

Lesson 12 Runoff Estimation– SCS Curve Number Method

12.1 Introduction

The soil conservation service curve number (SCS-CN) method was developed in 1954 and is documented in section 4 of the National Engineering Handbook (NEH-4) published by the Soil Conservation Service (now called as Natural Resources Conservation Service) of the United States Department of Agriculture (USDA) in 1956.

It is one of the most popular methods for computing the volume of surface runoff for a given rainfall event from small agricultural, forest and urban watersheds. The method is simple, easy to understand and use; stable, and useful for ungauged watersheds. The primary reasons for its wide applicability and acceptability lies in the fact that it accounts for most runoff producing watershed characteristics: soil type, land use/treatment, surface condition and antecedent moisture condition.

12.2 Determination of Curve Number

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of the actual amount of direct surface runoff (Q) to the total rainfall (P) (or maximum potential surface runoff) to the ratio of the amount of actual infiltration (F) to the amount of the potential maximum retention (S). The second hypothesis relates the initial abstraction (Ia) to the potential maximum retention, thus the SCS-CN method consists of:

(a) Water Balance Equation:

$P = I_a + F + Q$ (12.1)

(b) Proportional Equality Hypothesis:

$Q/P-Ia = F/S$ (12.2)

(c) I_a -S hypothesis

$I_a = \lambda S$ (12.3)

Where P= total rainfall; Ia =initial abstraction; F= cumulative infiltration excluding Ia; Q= direct runoff; and S= potential maximum retention or infiltration.

Combining equations 12.1 and 12.2, it becomes

$Q = (P - I_a)^2/(P - I_a + S)$ (12.4)

Equation is valid for P ≥ Ia. For λ = 0.2, the equation can be written as:

$Q = (P - 0.2 S)^2/(P + 0.8 S)$ (12.5)
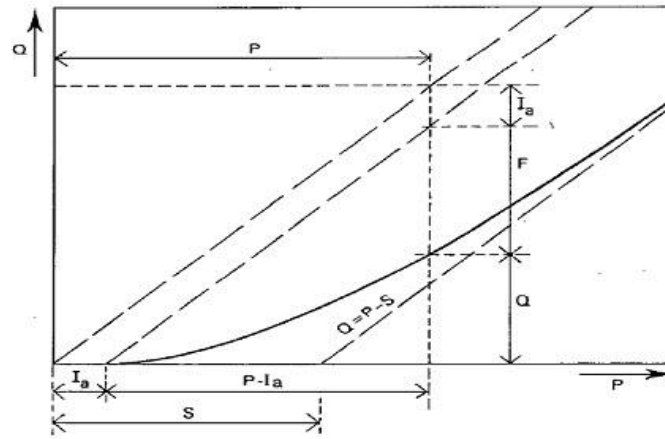
Fig. 12.1. Accumulated runoff Q versus accumulated rainfall P according to the Curve number Method. (Source: http://edepot.wur.nl/183157)

Thus the existing SCS-CN method is a one parameter model for computing surface runoff from daily storm rainfall, for the method was originally developed using daily rainfall-runoff data of annual extreme flows. S is a constant and is the maximum difference of (P-Q) that can occur for the given storm and watershed condition. S is limited by either the rate of infiltration at the soil surface or the amount of water storage available in the soil profile, whichever gives the smaller S value. Since parameter S can vary in the range of $0 \leq S \leq \infty$, it is mapped into a dimensionless curve number(CN), varying in a more workable range $0 \leq CN \leq 100$, as follows: (Actually, to make Eq. 12.6 mathematically workable, the CN limit should be $0 < CN \leq 100$)

S = (1000/CN) -10   (12.6)

The underlying difference between S and CN is that the former is a dimensional quantity (L) whereas the latter is a non-dimensionless quantity. The CN theoretically varies from 0 to 100.
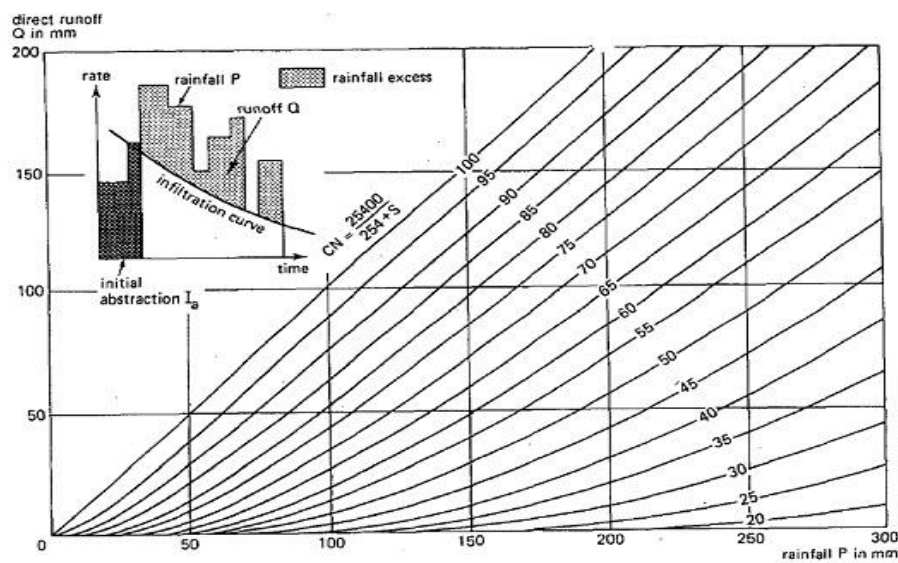
Fig. 12.2. Graphical solution of equation 12.4 showing runoff depth Q as a function of rainfall depth P and curve number. Source: http://edepot.wur.nl/183157)

12.3 Factors Affecting SCS Curve Number

The Curve Number is a dimensionless parameter indicating the runoff response characteristic of a drainage basin. In the Curve Number Method, the CN is related to land use, land treatment, hydrological condition, hydrological soil group, and antecedent soil moisture condition in the drainage basin.

(a) Land Use or Cover

Land use represents the surface conditions in a drainage basin and is related to the degree of cover. In the SCS method, the following categories are distinguished:

Fallow- is the agricultural land use with the highest potential for runoff because the land is kept bare; Row crops- are field crops planted in rows far enough apart that most of the soil surface is directly exposed to rainfall; Small grain- planted in rows close enough that the soil surface is not directly exposed to rainfall; Close-seeded legumes or rotational meadow- are either planted in close rows or broadcasted. This kind of cover usually protects the soil throughout the year; Pasture range- is native grassland used for grazing, whereas meadow is grassland protected from grazing and generally mown for hay; Woodlands- are usually small isolated groves of trees being raised for farm use.

(b) Practice in relation to Hydrological Condition

Land treatment applies mainly to agricultural land uses. It includes mechanical practices such as contouring or terracing, and management practices such as rotation of crops, grazing control, or burning.

Rotations are planned sequences of crops (row crops, small grain, and close-seeded legumes or rotational meadow). Hydrologically rotations range from poor to good. Poor rotations are generally one-crop land uses (monoculture) or combinations of row crops, small grains, and fallow. Good rotations generally contain close-seeded legumes or grass.

For grazing control and burning (pasture range and forest), the hydrological condition is classified as poor, fair, or good. Pasture range is classified as poor when heavily grazed and less than half the area is covered; as fair when not heavily grazed and between one-half to three-quarters of the area is covered; and as good when lightly grazed and more than three-quarters of the area is covered. Woodlands are classified as poor when heavily grazed or regularly burned; as fair when grazed but not burned; and as good when protected from grazing.

(c) Hydrological Soil Group

Soil properties greatly influence the amount of runoff. In the SCS method, these properties are represented by a hydrological parameter: the minimum rate of infiltration obtained for a bare soil after prolonged wetting. The influence of both the soil's surface condition (infiltration rate) and its horizon (transmission rate) are thereby included. This parameter, which indicates a soil's runoff potential, is the qualitative basis of the classification of all soils into four groups. The Hydrological Soil Groups, as defined in the SCS-CN method, are:

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Group A: Soils having high infiltration rates even when thoroughly wetted and a high rate of water transmission. Examples are deep, well to excessively drained sands or gravels.

Group B: Soils having moderate infiltration rates when thoroughly wetted and a moderate rate of water transmission. Examples are moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.

Group C: Soils having low infiltration rates when thoroughly wetted and a low rate of water transmission. Examples are soils with a layer that impedes the downward movement of water or soils of moderately fine to fine texture.

Group D: Soils having very low infiltration rates when thoroughly wetted and a very low rate of water transmission. Examples are clayey soils with a high swelling potential, soils with a permanently high water table, soils with a clay pan or clay layer at or near the surface, or shallow soils over nearly impervious material. Table 12.1 shows Land use categories and associated curves number, according to soil group; commercial land has different curve number.

Table 12.1. Land Use Categories and Associated Curve Numbers

Description	Average % Impervious	Curve Number by Hydrologic Soil Group				Typical Land Uses
		A	B	C	D	
Residential (High Density)	65	77	85	90	92	Multi-family Apartments, Trailer Parks
Residential (Med. Density)	30	57	72	81	86	Single-Family, Plot Size 0.1 to 0.4 ha
Residential (Low Density)	15	48	66	78	83	Single-Family, Plot Size 0.4 ha and Greater
Commercial	85	89	92	94	95	Strip Commercial, Shopping Centers, Convenience Stores
Industrial	72	81	88	91	93	Light Industrial, Schools, Prisons, Treatment Plants
Disturbed/Transitional	5	76	85	89	91	Gravel Parking, Quarries, Land Under Development
Agricultural	5	67	77	83	87	Cultivated Land, Row crops, Broadcast Legumes
Open Land	5	39	61	74	80	Parks, Golf Courses, Greenways, Grazed Pasture
Meadow	5	30	58	71	78	Hay Fields, Tall Grass, Un-grazed Pasture

Woods (Thick Cover)	5	30	55	70	77	Forest Litter and Brush adequately cover soil
Woods (Thin Cover)	5	43	65	76	82	Light Woods, Woods-Grass combination, Tree Farms
Impervious	95	98	98	98	98	Paved Parking, Shopping Malls, Major Roadways
Water	100	100	100	100	100	Water Bodies, Lakes, Ponds, Wetlands

(Source: http://proceedings.esri.com/library/userconf/proc00/professional/papers/pap657/p657.htm)

(d) Antecedent Moisture Condition

The soil moisture condition in the drainage basin before runoff occurs is another important factor influencing the final CN value. In the Curve Number Method, the soil moisture condition is classified in to three Antecedent Moisture Condition (AMC) Classes:

AMC I: The soils in the drainage basin are practically dry (i.e. the soil moisture content is at wilting point).

AMC II: Average condition.

AMC III: The soils in the drainage basins are practically saturated from antecedent rainfalls (i.e. the soil moisture content is at field capacity).

These classes are based on the 5-day antecedent rainfall (i.e. the accumulated total rainfall preceding the runoff under consideration), as illustrated in Table 12.2. In the original SCS method, a distinction was made between the dormant and the growing season to allow for differences in evapotranspiration.

Table 12.2. Seasonal rainfall limits for AMC classes (after soil conservation Service, 1972)

Antecedent Moisture Condition Class	5-day antecedent rainfall (mm)		
	Dormant season	Growing season	Average
1	2	3	4
I	< 13	< 36	< 23
II	13 – 28	36 – 53	23 – 40
III	> 28	> 53	> 40

(Source: http://edepot.wur.nl/183157)

(e) Agricultural Management Practices

Agricultural management system involves different types of tillage, vegetation, and surface cover. Moldboard Plough increases soil porosity from 10-20%, depending on the soil texture and, in turn, increases infiltration rates as compared to those for the non-tilled soils. Also, an increase in the organic matter content in the soil lowers the bulk density or increases porosity, and hence increases infiltration and in turn, decreases the runoff potential.

(f) Initial Abstraction and Climate

The initial abstraction consists of interception, surface detention, evaporation, and infiltration. The water held by interception, surface detention, and the infiltration at the beginning of a storm finally goes back to atmosphere through evaporation. The effect of the climatic condition of watershed is accounted for by the existing SCS-CN method in terms of the initial abstraction. It is the amount of initial abstraction for a given rainfall amount in watershed. Thus the initial abstraction reduces the runoff potential of the watershed and the curve number.

(g) Rainfall Intensity and Duration and Turbidity

A high intensity rainfall or raindrop breaks down the soil structure to make soil fines move into the soil surface or near-surface pores, leading to the formation of crust that impedes infiltration. The crust formation actually decreases the effective soil depth responsible for infiltration and also the soil porosity, decreases S or increases CN. It is for this reason that a fallow land exposed to rain, produce a higher runoff for a given rainfall amount than does the unexposed or covered land. The term turbidity refers to impurities of water that affect infiltration by the process of clogging of soil pores and consequently, affecting the soil conductivity or ease with which water is transmitted into the soil. The contaminated water with dissolved minerals, such as salts, affects the soil structure and consequently, infiltration.

Table 12.3. Rainfall depth and corresponding direct runoff depth as a function of rainfall duration and AMC condition for a design return period of 10 years

Design rainfall			Direct runoff	
Duration (h)	Intensity (mm/h)	Depth (mm)	Depth (mm) AMC II	Depth (mm) AMC III
1	2	3	4	5
1	88	88	25	50
2	53	106	37	66
3	39	117	44	76
4	32	128	52	86
5	27	135	58	93
24	8.7	209	118	163
48	5.6	269	172	222
72	4.6	331	229	283

(Source: http://edepot.wur.nl/183157)

12.4 Advantage, Scope and Limitation of SCS-CN Method

- The SCS-CN method has several advantages over other methods.

- It is a simple conceptual method for estimation of the direct runoff amount from a storm rainfall amount, and it is well supported by empirical data.

- The method relies on only one parameter, the curve number CN, which is a function of the major runoff-producing watershed characteristics.

- It is fairly well documented for its inputs (soil, land use/treatment, surface condition, and antecedent moisture condition),

- Its features are readily grasped, well establish, and accepted for use in the United States and other countries.

Limitation

- It does not contain any expression for time and ignore the impact of rainfall intensity and its temporal distribution.

- Time was incorporated in the method because (a) sufficiently reliable data were not available to describe infiltration rates for a wide range of complexes and (b) there was no reliable method available for distributing rainfall in time.

- The SCS-CN method has evolved as a result of research and field monitoring over the years. In many situations, it has given acceptable results. Its further refinement has been a continuous process.

- There is lack of clear guidance on how to vary antecedent moisture condition, especially for lower curve numbers and rainfall amount.

- The method was originally developed for agricultural sites; it performs best on these watersheds, fairly on range sites, and poorly in forest sites.

Prediction Errors Related to the Use of Single Composite CN Values

Grove et al. (1998) in their study investigated the effect of using single composite CN values instead of weighted runoff estimates, indicating that significant errors in runoff estimates can occur when composited rather than distributed CN are used. Lantz and Hawkins (2001) also discussed the possible errors caused by the use of a single composite CN value. The main reason for the errors produced using the composite CN value instead of weighted-Q is the non-linear form of the SCS-CN formula.

Scope of the SCS-CN concept in hydrology

The existing SCS-CN method has been widely used for computing the direct runoff volume from a given rainfall amount. Apart from such an application the method has also been applied to long term hydrologic simulation but only to a limited extent.

Gulley and Ravine Control Structures

1. Computation of Infiltration and DSRO (direct surface runoff) Volumes

The determination of infiltration and runoff volumes is vital to watershed management activities. For computing infiltration and runoff using the SCS-CN, the pertinent parameters are potential maximum retention, S, or curve number, CN.

2. Computation of Infiltration Rates

The problem of computing infiltration rates has been recognized and has been discussed in hydrologic literature. Although the SCS-CN method is construed as an infiltration model, it has not yet been employed in field for computing infiltration rates.

Time-distributed event-based hydrologic simulation

Flood studies often require determination of the peak flow rate and the time of concentration. The lack of short-term real time data can be attributed to the development of the SCS-CN method-based infiltration model with a routing mechanism which will make it possible to compute runoff rates at discrete times during a storm.

3. Long Term Hydrological Simulation

Long term hydrologic simulation is required for analyses of water availability. The SCS-CN method has witnessed only a few applications. With the enhanced understanding of the SCS-CN parameters, it is possible to reasonably simulate daily flows for a much longer period, applying the soil moisture balance.

4. Sediment yield

Sediment has been characterized as the largest carrier of pollutants to receiving water bodies. Much of the sediment carried by streams originates in upland areas. Many methods have been developed for estimation of erosion and sediment yield from agriculture, urban and rural watersheds. One of the most popular methods is the empirically derived universal soil loss equation (USLE). A close examination of this equation suggested that the SCS-CN methodology can be employed to derive a sediment yield equation which is similar to USLE.

Lesson 13 Runoff Hydrograph - I

13.1 Introduction

A plot of the discharge in a stream plotted chronologically against time is called a Hydrograph. Hydrograph is the graphical representation of the response of the watershed for a given storm as input.

Chow (1964) stated that hydrograph can be regarded as an integral expression of physiographic and climatic characteristics that govern the relation between the rainfall and runoff of a particular drainage basin. It shows the time distribution of runoff at the point of measurement, defining the complexities of the basin characteristics by a single empirical curve. Generally, a stage recorder is installed in the channel to obtain the hydrograph of the stream flow.

When a rainstorm occurs, a part of it remains on the land surface after accounting for the initial abstraction and infiltration losses. This reaches the drainage channels or the stream through overland and channel flow of rainfall excess. The process of overland and channel flows of rainfall excess is known as translation. During the process of translation, storage is built up both in the overland and channel flow phases, and the storage gradually depletes after the rainfall stops. Thus, there is a time lag between the time of initiation of rainfall and the time when the rainfall excess reaches the outlet of the watershed, where the runoff is measured by a stage level recorder or by manually noting the stage of flow at different times.

The intensity of rainfall, the time of concentration of the watershed, the succession of storms, the groundwater recession pattern and similar other factors determine the peak of a hydrograph. A concentrated storm of rainfall over an isolated duration produces a single-peaked skewed-distributed hydrograph. In other cases when storm rainfalls are separated by short time intervals or when rain storms of varying intensities occur over an extended time period, multiple-peaked hydrographs are likely to occur. A multiple peaked hydrograph can be separated into a number of single peaked hydrograph, when required for analysis.

13.2 Flood Hydrograph

Flood hydrograph is the hydrograph generated due to storm runoff. It is also called storm hydrograph or runoff hydrograph. Fig.13.1 shows the flood hydrograph. The flood hydrograph consists of all the three phases of runoff, viz. surface runoff, inter flow and base flow.
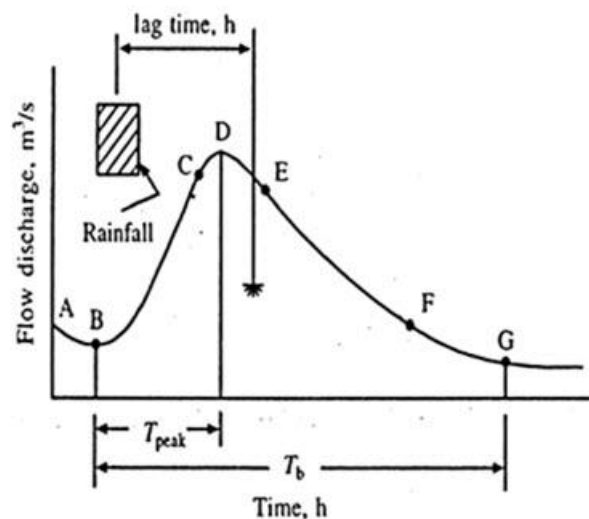
Fig. 13.1. Flood hydrograph. (Sources: Das, 2002)

Depending upon the unit of time involved, the hydrographs are classified as:

(a) Annual hydrograph

(b) Monthly hydrograph

(c) Seasonal hydrograph

(d) Flood hydrograph

(a) Annual Hydrograph

Annual hydrograph represents the variation of daily or weekly or 10 daily mean flow over a year.

(b) Monthly Hydrograph

Monthly hydrograph represents the variation of daily mean flows over a month.

(c) Seasonal Hydrograph

Seasonal hydrograph represents the variation of the discharge in a particular season such as the monsoon season or dry season.

(d) Flood Hydrograph

Flood hydrograph or simply hydrograph represents stream flow due to a storm over a catchment.

Each of these types has specific applications. Annual or seasonal hydrograph is used in calculating the surface water potential of stream, reservoir studies and drought studies. Whereas, flood hydrographs are essential in analyzing stream characteristics associated with floods.

13.3 Factors Affecting Flood Hydrograph

The factors that affect the shape of the hydrograph can be broadly grouped into two categories as given below:

(i) Physiographic factors

(ii) Climatic factors

(i) Physiographic Factors

The physiographic factors are:

(1) Basin Characteristics:

(a) Shape

(b) Size

(c) Slope

(d) Drainage density

(e) Nature of the valley

(f) Elevation

(2) Infiltration Characteristics:

(a) Land use/ land cover

(b) Soil type and geological conditions

(c) Lake, swamps and other storages

(3) Channel Characteristics:

(a) Channel cross section

(b) Roughness

(c) Storage capacity

(ii) Climatic Factors:

The climatic factors are

(1) Storm Characteristics:

(a) Precipitation

(b) Intensity

(c) Duration

(d) Magnitude

(e) Movement of storm

(2) Initial Loss

(3) Evaporation

The rising limb of the hydrograph is dependent upon both physiographic and climatic factors, whereas; the recession limb depends only upon physiographic factors.

Some of the important physiographic and climatic factors are describe below.

(i) Physiographic Factors:

- **Shape of the Basin**

The effect of catchment shape on hydrograph is illustrated in fig. 13.2.
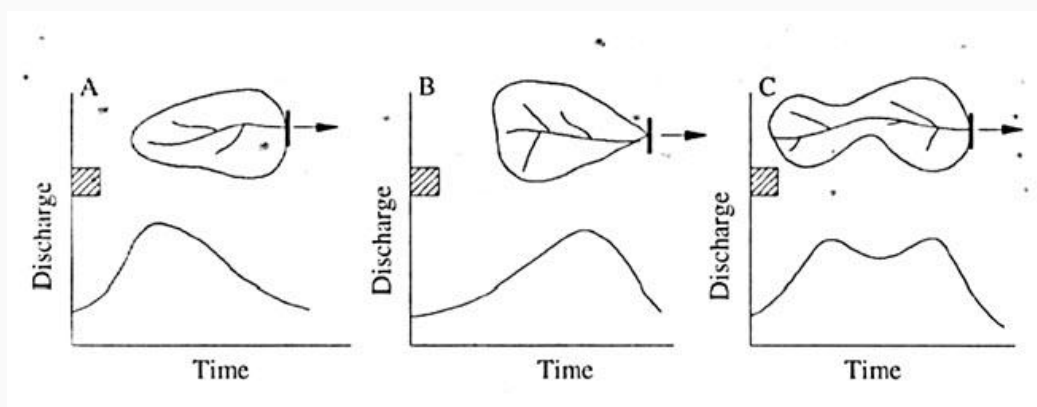
Fig. 13.2. Effect of catchment shape on hydrograph. (Sources: Subramanya, 1994)

The Shape of the basins influences the time taken for water from the remote parts of the catchment to arrive at outlet. Thus the occurrence of peak and hence the shape of hydrograph are affected by basin shape. Fan shaped, that is semi-circular shaped catchments give sharp and narrow hydrographs while the elongated catchments give broad and low peaked hydrographs.

- **Size of the Basins**

Small basins behave differently from large ones in terms of the relative importance of various phases of runoff phenomenon. Effect of basin size is illustrated in Fig. 13.3. In small basins the overland flow phase is predominant over the channel flow, whereas; in large basins channel flow is predominant. The peak is high in a large basin than in a small basin as peak discharge is found to vary as A^n, where A is the catchment area and n is an exponent whose value is less than unity, being about 0.5. The base of hydrograph from larger basins will be larger than those of corresponding hydrographs from smaller basins.
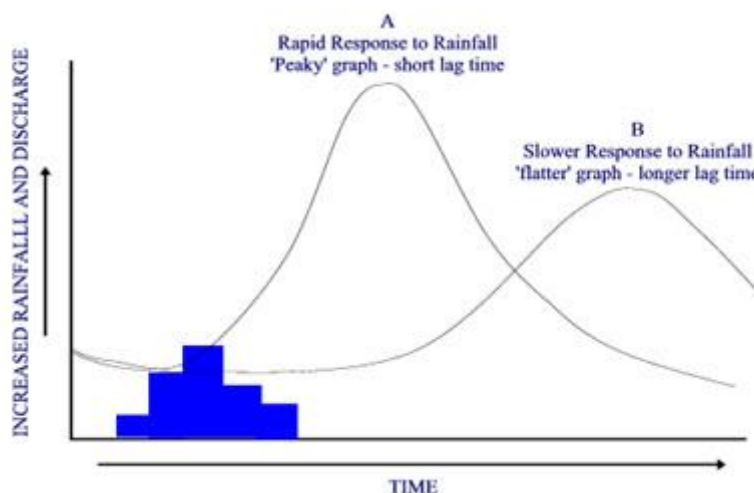
Fig. 13.3. Effect of basin size on hydrograph. (Sources: https://www.cgz.e2bn.net)

- **Slope**

The slope of the main stream controls the velocity of flow in the channel. As the recession limb of the hydrograph represents the depletion of storage, the stream channel slope will have a pronounced effect on this part of the hydrograph. Large stream slopes give rise to quicker depletion of storage and hence result in steeper recession limb of hydrograph and smaller time base. The effect of channel slope is illustrated in fig. 13.4.
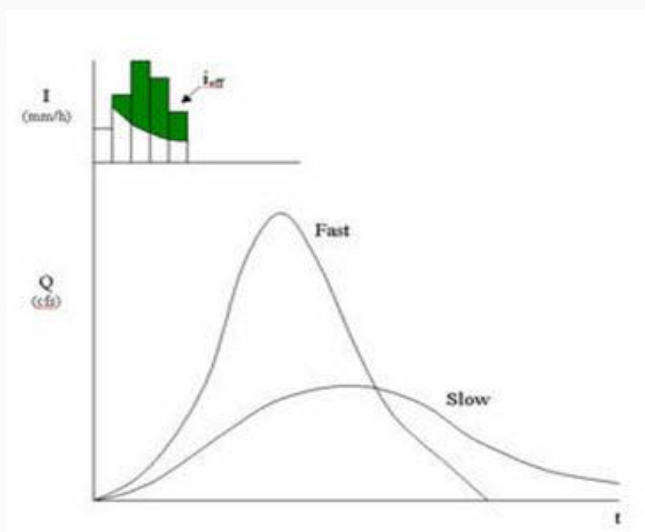
Fig. 13.4. The effect of channel slope on hydrograph. (Source: https://www.daad.wb.tu-harburg.de)

The basin slope is important in small catchment where the overland flow is more important. In such cases the steeper slope of the catchment results in larger peak discharge.

- **Drainage Density**

The drainage density is a measure of the total length of well-defined channels that drain the catchment (sometimes measured as the blue lines representing the streams on a topographic

map). Drainage density is defined as the sum of the lengths of all of the channels (km) divided by the total catchment area (km^2). This ratio can be determined from topographical maps. The effect of drainage density on hydrograph is illustrated in Fig.13.5. Drainage density affects the response of the catchment to rainfall. High densities usually allow fast runoff removal. Therefore, hydrographs having greater peaks and with shorter durations are expected for catchments with higher drainage densities. In catchment with smaller drainage densities, the overland flow is predominant and the resulting hydrograph is squat with a slowly rising limb.
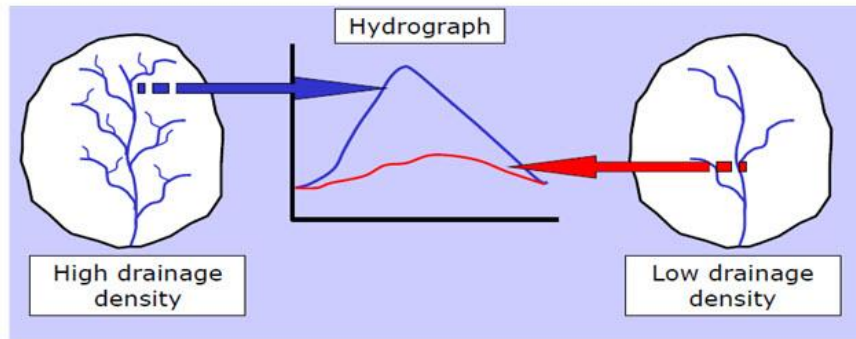
Fig. 13.5 Effect of drainage densities on hydrograph. (Source: http://www.lanarkgrammargeography.pbworks.com)

- **Land Use**

Vegetation and forests increase the infiltration and storage capacities of the soils. Further they cause considerable retardance to the overland flow. Thus vegetal cover reduces the peak flow. In general, for two catchments of equal area, other factors being identical, the peak discharge is higher for a catchment that has a lower density of forests cover. The effect of land use on hydrograph is shows in fig. 13.6.
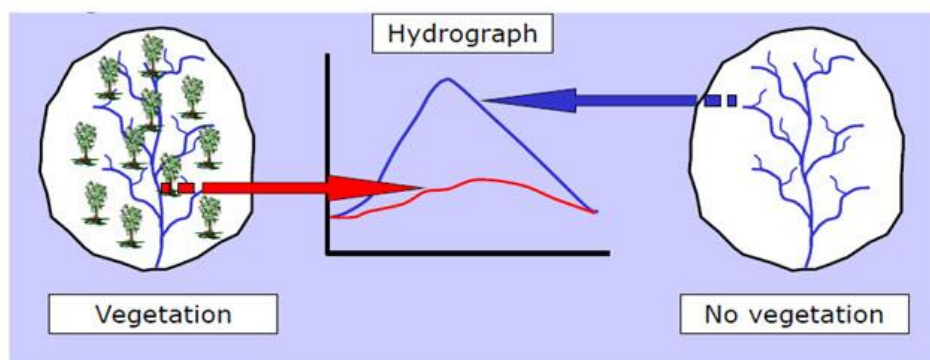
Fig. 13.6 Effect of land use on hydrograph. (Source: http://www.lanarkgrammargeography.pbworks.com)

- **Channel Roughness**

Roughness affects the velocity of overland flow and stream flow. A rough channel will cause smaller peaks than a smooth channel. For a given discharge, stage levels (water surface elevations) in a stream are higher for rough channels.

- **Storage Capacity**

Storage can take place within the streambed, flood plains, marshes, lakes, or in artificial features such as storm water management facilities and reservoirs. Storage also takes place in the impoundments created upstream of road crossings (e.g., bridges, and culverts). In general, storage reduces and delays the peaks and increases the duration of runoff.

(ii) Climatic Factors

Among the climatic factors the intensity, duration and direction of storm movement are the three important ones affecting the shape of flood hydrograph.

- **Intensity**

For a given duration, the peak and volume of the surface runoff are essentially proportional to the intensity of rainfall.

- **Duration**

The duration of storm for a given intensity also has a direct proportional effect on the volume of runoff. The effect of duration is reflected in the rising limb of the peak flow.

- **Storm Movement**

If the storm moves from upstream of the catchment to the downstream end, there will be a quicker concentration of flow at the basin outlet. This results in a peaked hydrograph. Conversely, if the storm movement is up the catchment, the resulting hydrograph will be a lower peak and longer time base.

Lesson 14 Runoff Hydrograph - II

14.1 Components of Hydrograph

The essential components of hydrograph are illustrated in fig. 14.1 and described below

(i) Rising limb

(ii) Crest segment

(iii) Recession limb

(i) Rising Limb

The rising limb of hydrograph represents the increase in discharge due to gradual building up of storage in channels over the catchment surface. Its shape depends on the distribution of rainfall intensity, the duration, the antecedent moisture condition of the soil and the translation of runoff from the drainage basin represented by time-area diagram. At the beginning, there is only base flow (i.e., the ground water contribution to the stream) gradually depleting in an exponential form. After the storm commences, the initial loss like interception and infiltration are met and then surface flow begins. However, they occur simultaneously because runoff starts as soon as the top soil gets saturated with water. The hydrograph gradually rises and reaches the first point of inflection where, the slope of the rising limb decreases. The first point of inflection is the point at which discharge consists of flow from all channels and after this peak is possible. As indicated earlier in Lesson 13, the basin and storm characteristics control the shape of the rising limb of the hydrograph.

(ii) Crest Segment

The crest segment is one of the most important parts of a hydrograph as it contains the peak of the hydrograph, which represents the highest concentration of runoff from the watershed. Peak flow occurs after time to peak, which is measured from the point of rise or initiation time of rainfall to the peak flow. The time of peak with respect to initiation time of rainfall varies depending on the distribution pattern of rainfall over the watershed. Generally, the peak occurs after the rain has stopped, but sometimes, when the rainfall is of an advanced type with diminishing rainfall intensity, the peak flow occurs before the end of rainfall. Multiple peaks occur due to the development of multiple storms which are close to each other Fig.14.2). After peak flow, the hydrograph further declines and reaches the second point of inflection, at which slope of the hydrograph further changes, representing the condition of maximum storage or the point at which discharge consists of no direct rain water. This is the last point of crest segment. The second point of inflection is at a distance equal to the time of concentration of the watershed from the end of excess rainfall.

(iii) Recession Limb

The recession limb, which extends from the second point of inflection at the end of crest segment to the commencement of the natural groundwater flow, represents the withdrawal of water from the storage in the basin during the earlier phases of hydrograph. At this time groundwater and the water held in the vadose zone contributes more into the stream flow than at the beginning of the storm. But there after the groundwater table declines and the hydrograph again goes on depleting in the exponential form called ground water depletion curve. The recession limb is independent of storm characteristics and depends entirely on the basin characteristics.
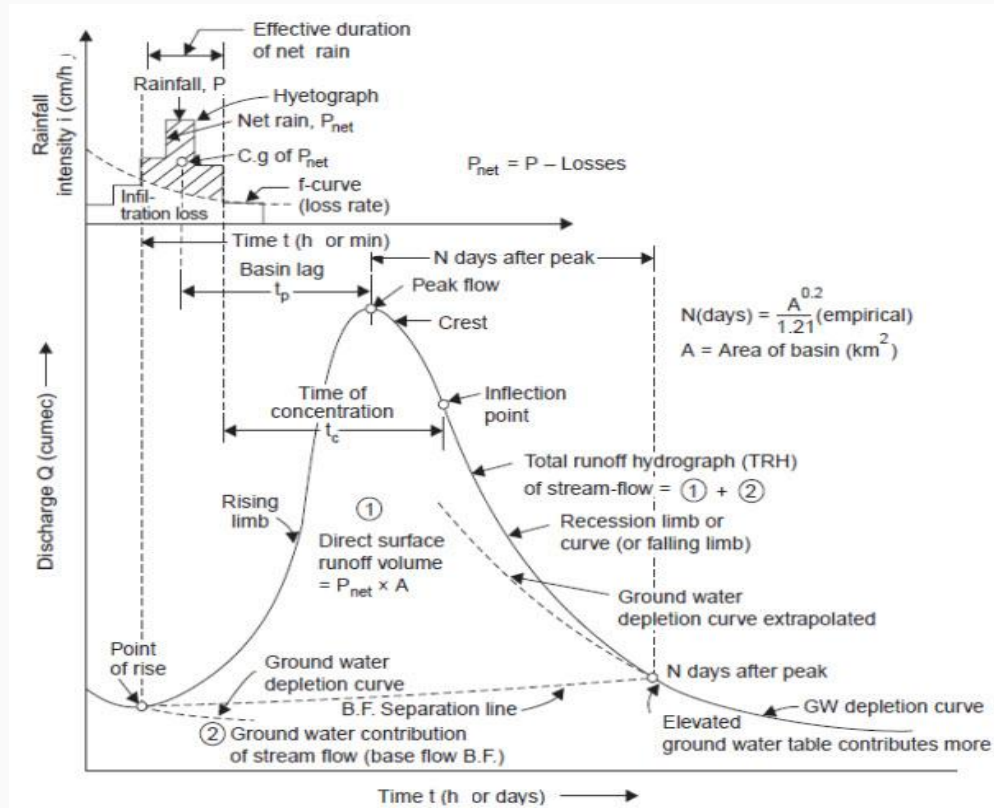
Fig. 14.1. Components of flood hydrograph. (Sources: Raghunath, 2006)
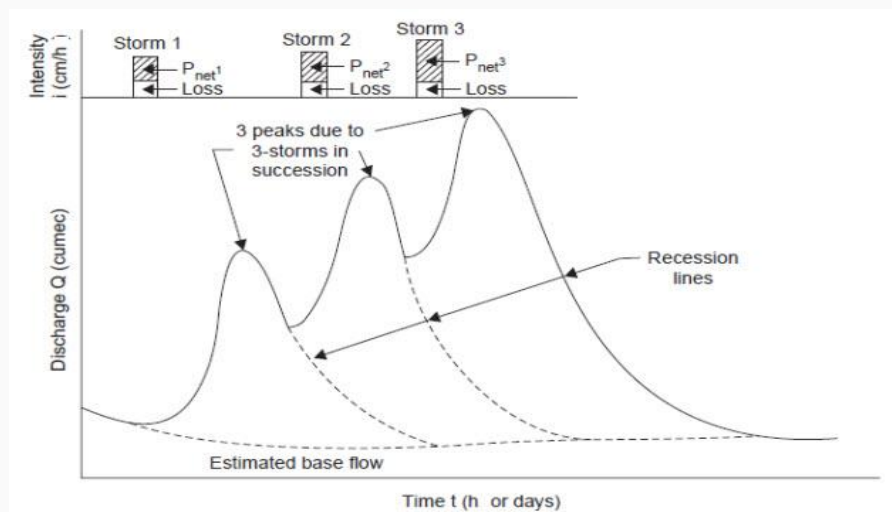
Fig. 14.2. Hydrograph with multiple peaks. (Sources: Raghunath, 2006)

14.2 Baseflow Separation

In many hydrograph analyses a relationship between the surface flow hydrograph and effective rainfall (that is rainfall minus losses) is sought to be established. The surface flow hydrograph is obtained from the total storm hydrograph by separating the quick response flow from the slow response runoff. It is usual to consider the interflow as a part of surface flow in view of its quick response. Thus only the base flow is to be deducted from the total storm hydrograph to obtain surface flow hydrograph. There are four methods of base flow separation that are commonly used. Different methods of base flow separation are illustrated in Fig. 14.3.
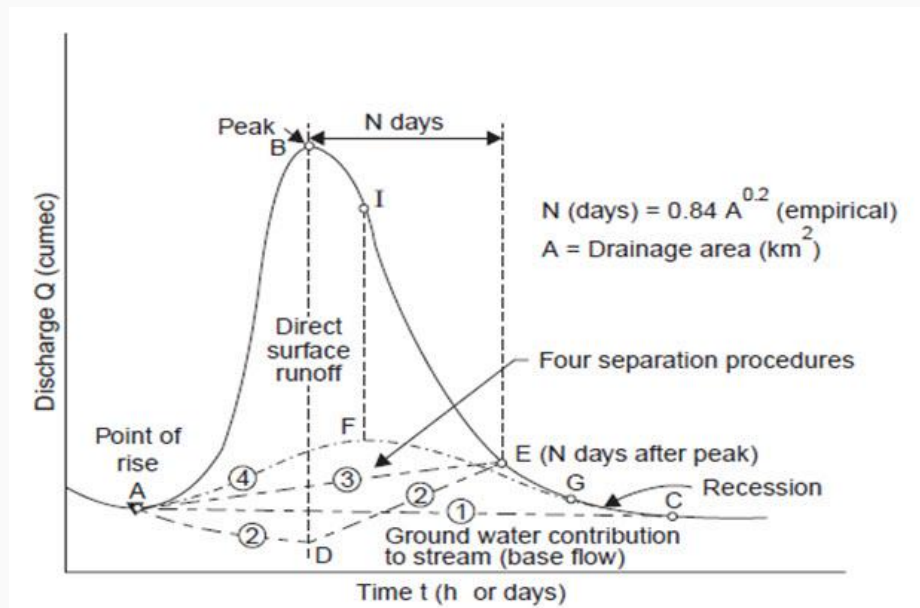
Fig. 14.3. Base flow separation. (Sources: Raghunath, 2006)

(1) Simply by drawing a line AC tangential to both the limbs at their lower portion. This method is very simple but is approximate and can be used only for preliminary estimates.

(2) Extending the recession curve existing prior to the occurrence of the storm up to the point D directly under the peak of the hydrograph and then drawing a straight line DE, where E is the point on the hydrograph N days after the peak, and N (in days) is given by

$$N = 0.83 \, A^{0.2}$$

Where, A= area of the drainage basins (km²)

(3) Simply by drawing a straight line AE, from the point of rise to the point E, on the hydrograph, N days after the peak.

(4) A line AFG is drawn, by projecting the groundwater recession curve after the storm backwards, to a point F directly under the second inflection point of the falling limb and sketch an arbitrary rising line from the point of the rise of the hydrograph to connect with the projected base flow recession. This method of separation is preferred where the ground water storage is relatively large and reaches the stream fairly rapidly, as in lime stone terrains.

Gulley and Ravine Control Structures

In all the above flow separation procedures, the area below the line constructed represents the base flow, which is the ground water contribution to the stream flow.
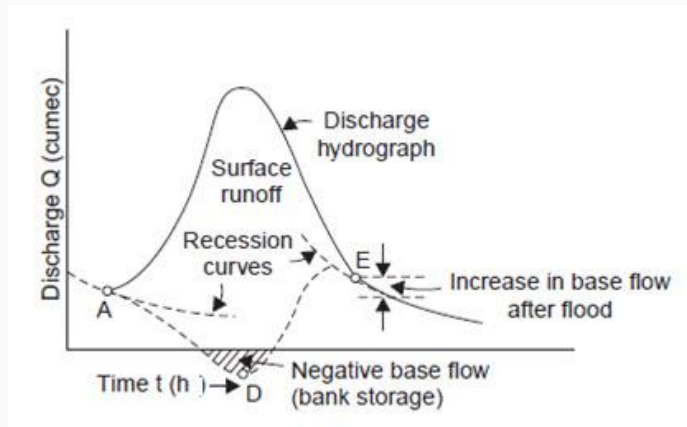
Fig. 14.4. Negative base flow. (Sources: Raghunath, 2006)
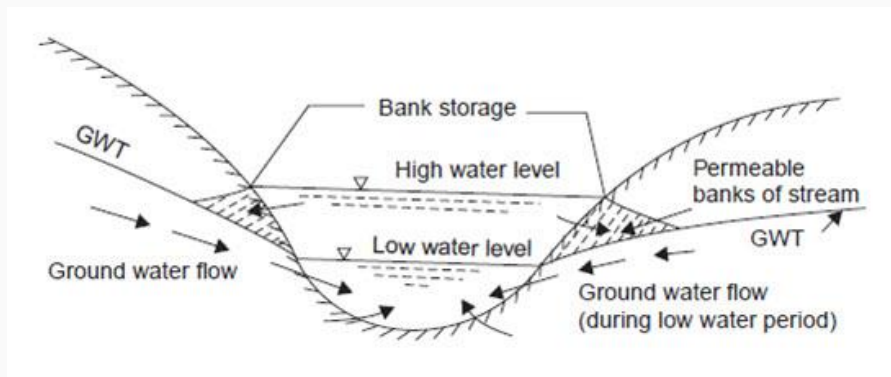
Fig. 14.5. Bank storage. (Sources: Raghunath, 2006)

In Fig. 14.4, ADE is the assumed base flow. Actually when the water level in the stream rises due to floods, the stream feeds the groundwater and the permeable boundaries (called bank storage Fig 14.5) and this is termed as negative base flow (Fig. 14.4).

14.3 Direct Runoff Hydrograph

Effective rainfall is the rainfall minus infiltration and initial losses. The resulting hyetograph is known as effective rainfall hyetograph (ERH). Fig. 14.6 shows the effective rainfall hyetograph. It is also known as hyetograph of rainfall excess or supra rainfall.

The excess rainfall is determined by the infiltration indices (as φ- index and W- index) as the infiltration indices are the average infiltration rate in the hyetograph above which the rainfall is the excess or effective rainfall and the volume of effective rainfall is equal to the surface runoff volume. Direct runoff hydrograph (DRH) is the hydrograph generated due to excess rainfall. The surface runoff hydrograph obtained after the base flow separation is also known as direct runoff hydrograph.
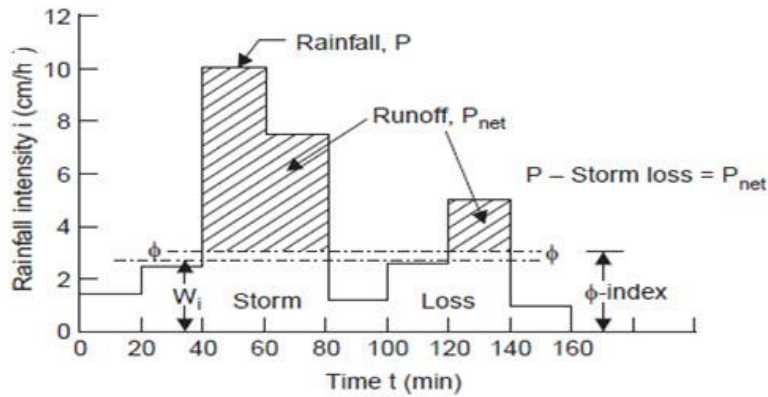
Fig. 14.6. Effective rainfall. (Sources: Raghunath, 2006)

Both ERH and DRH represent the same total quantity but in different units. Since ERH is usually in cm/h plotted against time, the area of ERH multiplied by the catchment area gives the total volume of direct runoff which is the same as area of DRH. Fig. 14.7 shows the direct runoff hydrograph.

Excess rainfall (P_e) = Rainfall (P) – Infiltration

Direct runoff = runoff – base flow So,

Volume of DRH = depth of rainfall excess × area of catchment

Area of DRH = DRH ordinate × time base of DRH

So, volume of DRH = Area of DRH
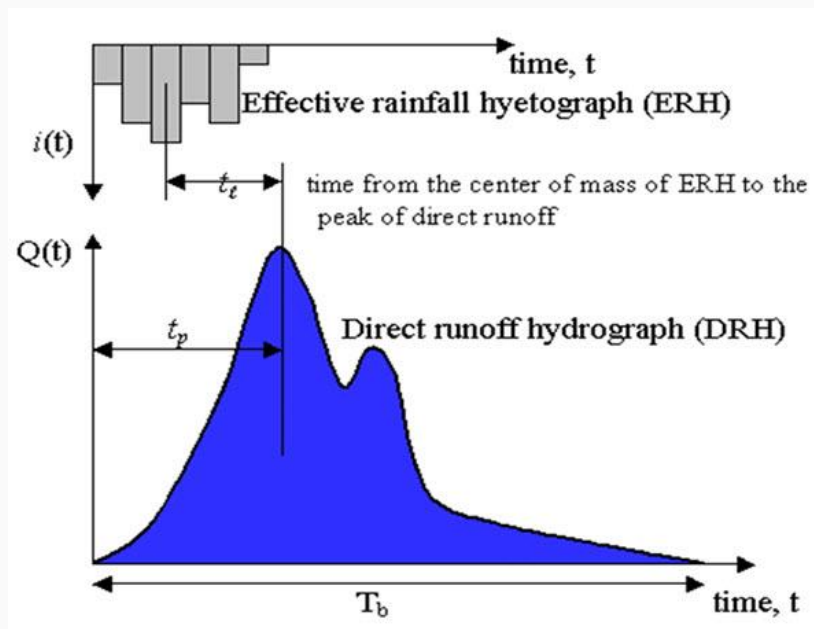
Fig. 14.7. Direct runoff hydrograph. (Sources: https: //www. rslabntu.net)

Where, t_p = time to peak flow from point of rising, T_b = base of hydrograph

Lesson 15 Unit Hydrograph - I

15.1 Unit Hydrograph Concept

The problem of predicting the flood hydrograph resulting from a known storm in a catchment, for which the flood hydrograph could not be recorded, has received considerable attention. For example, flood hydrograph may be needed for the 'design' storm, which may be the 10-year 4-h storm. Such storms are found from the analysis of rainfall data that are huge in volume. On the other hand, recorded hydrographs are always much fewer in number. A large number of methods are proposed to solve this problem and of them probably the most popular and widely used method is the unit-hydrograph method.

15.1.1 Unit Hydrograph

A unit hydrograph is defined (Subramanya, 1994) as the hydrograph of direct runoff resulting from one unit depth (1 cm) of rainfall excess occurring uniformly over the basin and at a uniform rate for a specified duration (D hours).

The definition of unit hydrograph implies the following:

1. The unit hydrograph represents the lumped response of the catchment to a unit rainfall excess of D-hour duration to produce a direct runoff hydrograph. It relates only the direct runoff to the rainfall excess. Hence, the volume of water contained in the unit hydrograph must be equal to the rainfall excess. As 1 cm depth of rainfall excess is considered the area of the unit hydrograph is equal to a volume given by 1 cm over the catchment.

2. The rainfall is considered to have an average intensity of excess rainfall of 1/D cm/h for the duration of D-h of the storm.

3. The distribution of the storm is considered to be uniform over the entire catchment.

15.1.2 Elements of Unit Hydrograph

The various elements of a unit hydrograph are shown in Fig.15.1
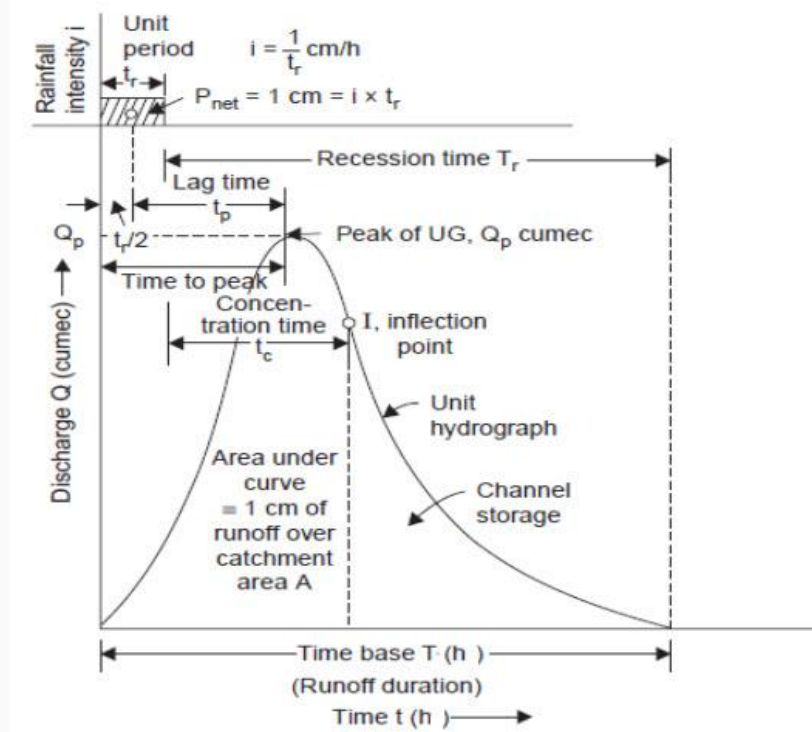
Fig. 15.1. Elements of unit hydrograph. (Sources: Raghunath, 2006)

(a)   Base width (T): The period of direct surface runoff (due to a unit storm) of the unit hydrograph is called the time base or the base width.

(b)   Unit storm: The storm of unit duration (i.e., duration of the unit hydrograph) regardless of its intensity is called unit storm.

(c)   Unit period: The time duration of the unit storm (i.e., the duration of the unit hydrograph) is called unit period.

(d) Lag time (t_p): The time from the center of a unit storm to the peak discharge of the corresponding unit hydrograph is called lag time.

(e)   Recession time (T_r): The duration of the direct surface runoff after the end of the excess or net rainfall, is called recession time in hydrograph analysis.

15.1.3 Assumptions of Unit Hydrograph

The following are the basic assumptions of the unit hydrograph:

1. Same Runoff Duration

For all unit storms of different intensities, the period of surface runoff (i.e., time base, base width or base period) is approximately the same, although they produce different runoff volumes (Fig. 15.2).

2. Proportional Ordinates

For unit storms of different intensities, the ordinates of the hydrograph at any given time are in the same proportion as the rainfall intensities (Fig. 15.2).

3. Principle of Superposition

If there is a continuous storm and/or isolated storms of uniform intensity net rain, they may be divided into unit storms and hydrographs of runoff for each storm obtained, and the ordinates added with the appropriate time lag to get the combined hydrograph (Fig. 15.3).\
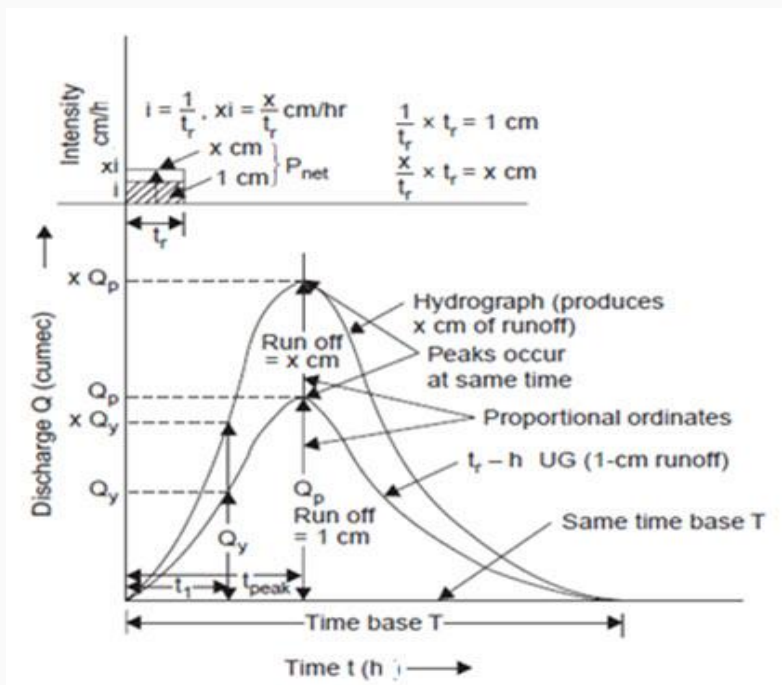
Fig. 15.2. Proportional ordinates and same time base. (Sources: Raghunath, 2006)
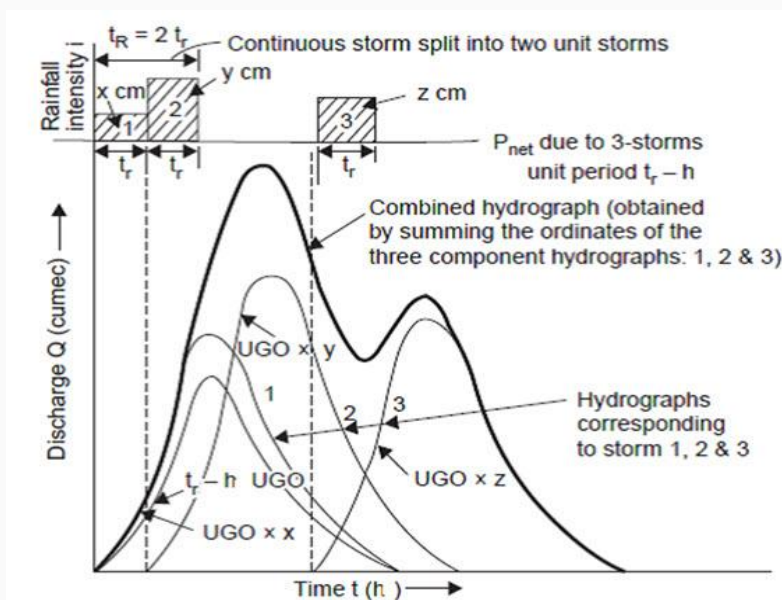
Fig. 15.3. Principle of superposition. (Sources: Raghunath, 2006)

4. Same Distribution Percentages

If the total period of surface runoff (i.e., time base or base width) is divided into equal time intervals the percentage of surface runoff that occurs during each of these periods will be the same for all unit storms of different intensities (Fig. 15.4).
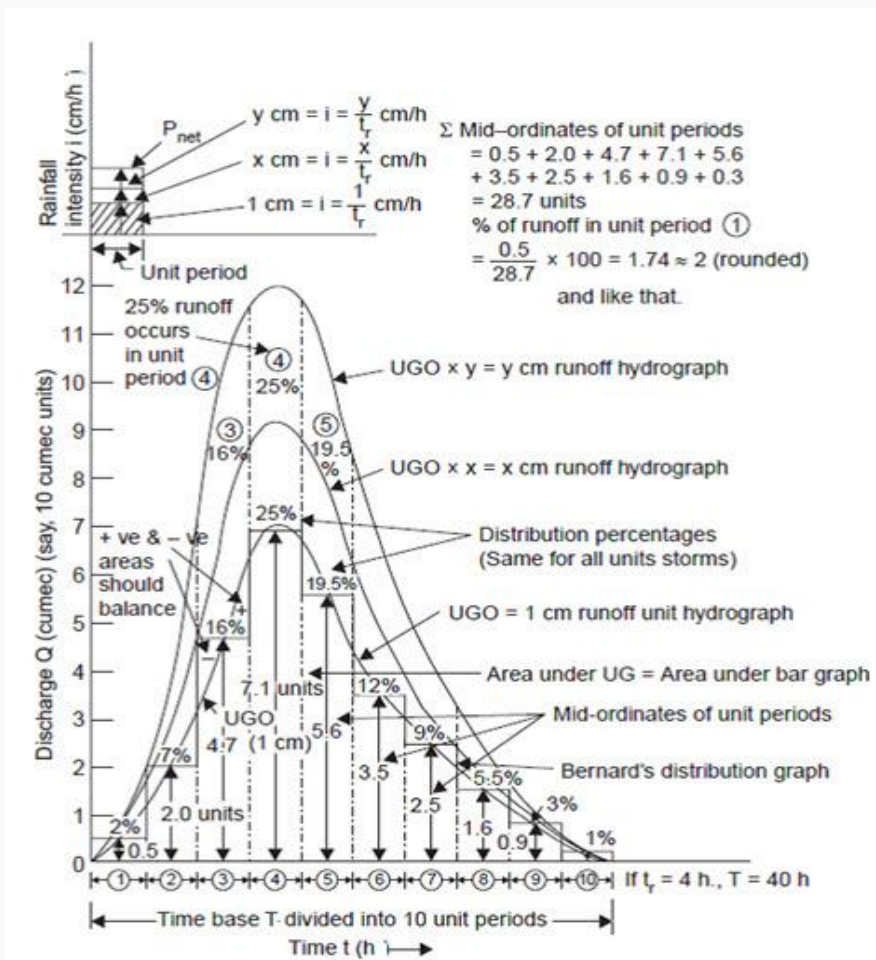
Fig. 15.4. Distribution percentage same for all unit storm. (Sources: Raghunath, 2006)

15.1.4 Derivation of the Unit Hydrograph

From the historical record, the mean daily stream flow data from a drainage basin is given below:

Date	Mean daily discharge (cumec)	Date	Mean daily discharge (cumec)
1978, Oct. 4	278	1978, Oct. 14	179
5	265	15	167
6	5350	16	157
7	8150	17	147
8	6580	18	139
9	1540	19	131
10	505	20	123
11	280	21	117
12	219	22	111
13	195	23	105
		24	100

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The following steps are adopted to derive a unit hydrograph from an observed flood hydrograph (Fig. 15.5).

Step1: Select from the records of isolated (single-peaked) intense storms, which had occurred uniformly over the catchment and produced flood hydrographs with appreciable runoff (>1cm, say, 8 to 16 cm). The unit period selected should be such that the excess rainfall (i.e., P_{net}) occurs fairly uniformly over the entire drainage basin. Larger unit periods are required for larger basins. The unit periods may be in the range of 15-30% of the 'peak time' period, i.e., the time from the beginning of surface runoff to the peak, and the typical unit periods may be 3, 6, 8, 12 hours. The time of concentration may be a little longer than the peak time. The unit storm is a storm of such duration that the period of surface runoff is not much lesser for any other storm of shorter duration.
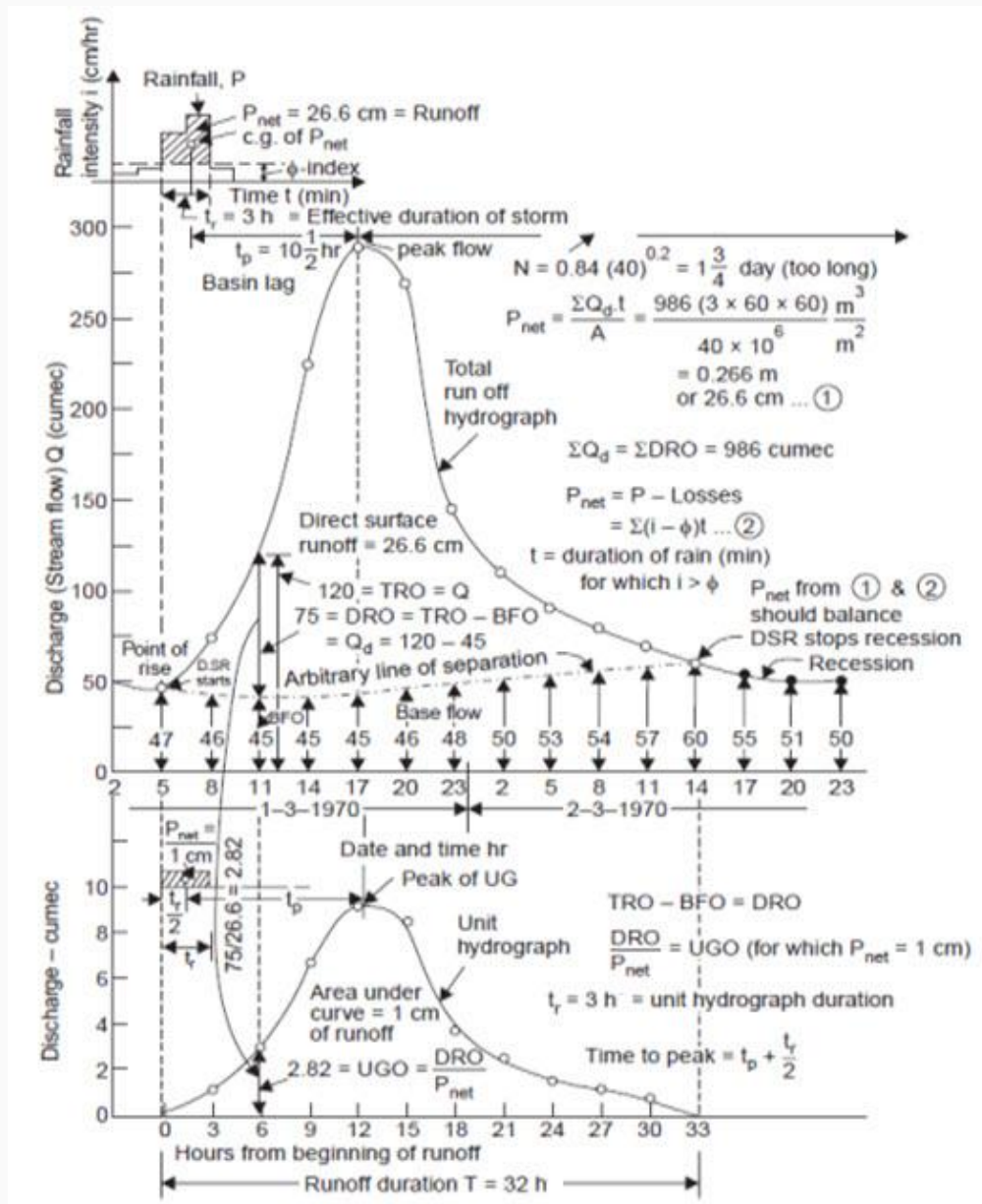
Fig. 15.5. Derivation of a unit hydrograph. (Sources: Raghunath, 2006)

Step 2: Select a flood hydrograph, which has resulted from a unit storm chosen in step (1) above.

Step 3: Separate the base flow from the total runoff (by the well-known base flow separation procedures).

Step 4: From the total runoff hydrograph ordinate (TRO) (at regular time intervals) deduct the corresponding base flow ordinate (BFO), to obtain the direct runoff ordinate (DRO).

Step 5: Divide the volume of direct runoff by the area of the drainage basin to obtain the net precipitation depth over the basin.

Step 6: Divide each direct runoff ordinate (DRO) by the net precipitation depth to obtain the unit hydrograph ordinate (UGO).

Step 7: Plot the unit hydrograph ordinate (UGO) against time since the beginning of direct runoff. This will give the unit hydrograph for the basin, for the duration of the unit storm (producing the flood hydrograph) selected in step (1) above.

In unit hydrograph derivation, such storms should be selected for which reliable rainfall and runoff data are available. The net rain graph (hyetograph of excess rain) should be determined by deducting the storm loss and adjusting such that the total volume of net storm rain is equal to the total volume of direct surface runoff. The unit hydrograph derived, which, when applied to the known net rain data, should yield the corresponding direct runoff hydrograph.

In many countries and regions and particularly for small agricultural catchments, flood hydrographs are not recorded and hence, the corresponding unit hydrographs cannot be derived. However, hydrologists have opined that a hydrograph derived for a given catchment may be applied to hydrologically similar catchments.

15.1.5 Alteration of Unit Hydrograph Duration

For the same catchment area, unit hydrographs of different durations may be required to match with the 'design' storm for a given purpose. For example, for designing a surface drainage system for a small agricultural catchment, the design storm may be the 5-year 1-h storm whereas for designing a drop spillway, it may be the 10-year 2 h storm. Usually, the return period and the duration of design storm are small when the losses involved if the designed system fails are also small. When the expected losses are more or of a serious nature (loss of cattle or human lives, damage to property), the return period and the duration are higher. For a hydrologically similar catchment of area different than the one for which the unit hydrograph has been derived, the time of concentration will differ. This will require the selection of the appropriate duration design storm. There are two methods for alteration of unit hydrograph duration

(1) Method of Superposition

If the desired long duration of the unit graph is an even multiple of the short, say a 3-hour unit graph is given and a 6-hour unit graph is required. Assume two consecutive unit storms,

producing a net rainfall of 1 cm each. Draw the two unit hydrographs, the second unit graph being lagged by 3 hours. Draw now the combined hydrograph by superposition. This combined hydrograph will now produce 2 cm in 6 hours. To obtain the 6-hour unit graph divide the ordinates of the combined hydrograph by 2, Fig. 15.6. It can be observed that this 6-hour unit graph derived has a longer time base by 3 hours than the 3-hour unit graph, because of a lower intensity storm for a longer time.
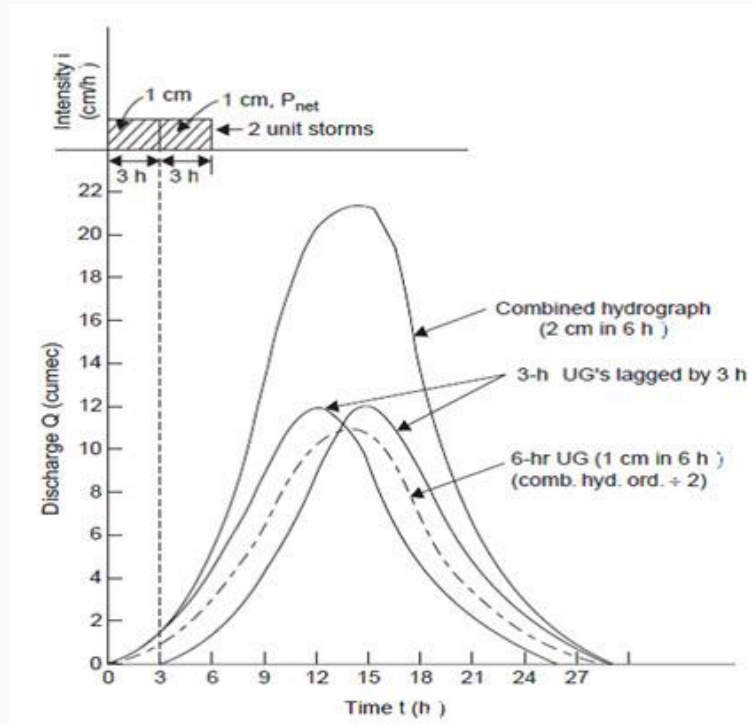

Fig. 15.6. Method of Superposition. (Sources: Raghunath. H.M., 2006)

(2) S-curve Technique

S-curve or the summation curve is the hydrograph of direct surface discharge that would result from a continuous succession of unit storms producing 1 cm in t_r–hour. (Fig.15.7). If the time base of the unit hydrograph is T hour, it reaches constant outflow (Q_e) at T hours, since 1 cm of net rain on the catchment is being supplied and removed every t_r hour and only T/t_r unit graphs are necessary to produce an S-curve and develop constant outflow given by

$$Q_e = \frac{2.78\ A}{t_r}$$

Where, Q_e = constant outflow (cumec), t_r = duration of unit graph (hour), A= area of the basin (km^2)
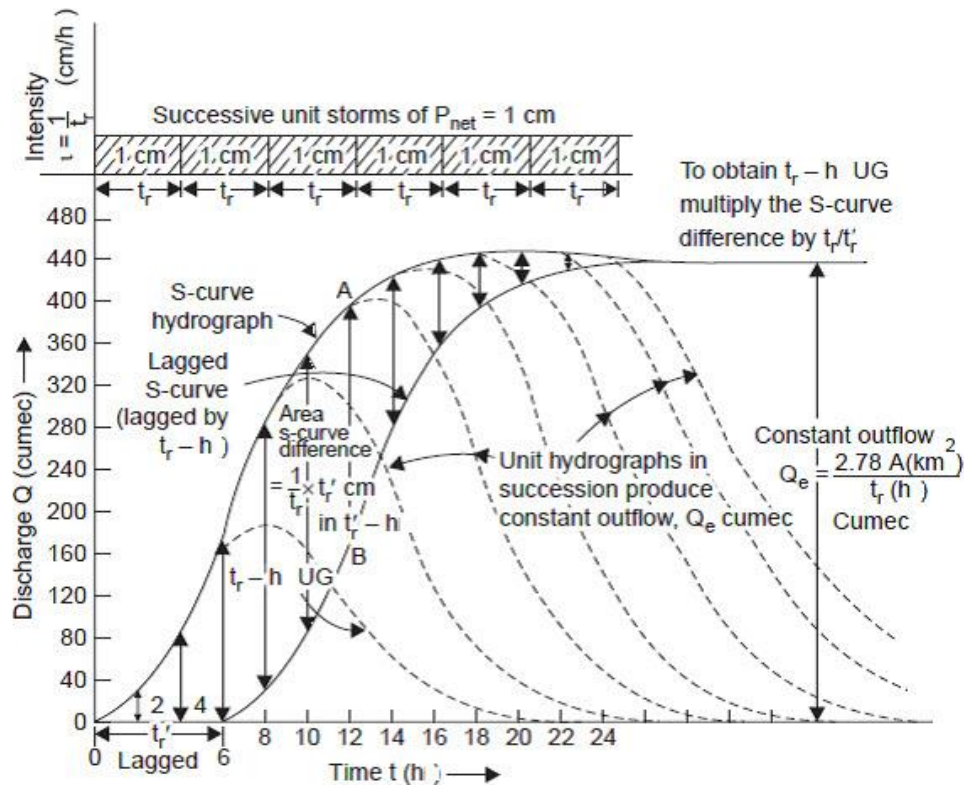
Fig. 15.7. S-curve technique. (Sources: Raghunath. H.M., 2006)

Given a t_r-hour unit graph, to derive a t_r'-hour unit graph ($t_r' \geq t_r$)—Shift the S-curve by the required duration t_r' along the time axis. The graphical difference between the ordinates of the two S-curves, i.e., the shaded area in Fig. 15.7 represents the runoff due to t_r' hours rain at an intensity of $1/t_r$ cm/hr, i.e., runoff of t_r'/t_r cm in t_r' hours. To obtain a runoff of 1 cm in t_r' hours (i.e., t_r'-hour UG), multiply the ordinates of the S-curve difference by t_r/t_r'. This technique may be used to alter the duration of the given unit hydrograph to a shorter or longer duration. The longer duration need not necessarily be a multiple of short.

15.2 Use and Limitation of Unit Hydrograph

As unit hydrographs establish a relationship between the ERH and DRH for a catchment, they are of immense value in the study of hydrology of a catchment.

They have wider use in

(i) Development of flood hydrograph for extreme rainfall magnitudes for the use in the design of the hydraulic structures.

(ii) Extension of flood flow records based on rainfall records.

(iii) Development of flood forecasting and warning system based on rainfall.

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However, there are some limitations in the use of unit hydrograph as:

(i) Unit hydrograph is applicable for catchment area between 2 km² to5000 km²

(ii) Precipitation must be from rainfall only. Snow-melt runoff cannot be satisfactorily represented by unit hydrograph.

(iii) The catchment should not have large storage in terms of tanks, ponds, large flood-bank storage, which effect the linear relationship between storage and discharge,

(iv) If the precipitation is non-uniform, unit hydrographs cannot be expected to give good results.

Lesson 16 Unit Hydrograph - II

16.1 Synthetic Unit Hydrograph

To develop unit hydrographs for a catchment, detailed information about the rainfall and the resulting flood hydrograph are needed. However, such information would be available only at a few locations and in a majority of catchments, especially those which are at a remote location; the data would normally be very scanty. In order to construct unit hydrograph for such areas, empirical equations of regional validity which relate the salient hydrograph characteristics to the basin characteristics are available. Unit hydrographs derived from such relationship are known as synthetic unit hydrographs. But these methods being based on empirical correlations are applicable only to the specific regions in which they were developed and should not be considered as general relationship for use in all regions.

Snyder's Method

Snyder (1938), based on a study of a large number of catchments in the Appalachian Highlands of eastern United States developed a set of empirical equations for synthetic unit hydrograph in those areas. These equations are used in the USA, and with some modifications in many other countries, and constitute what is known as Snyder's synthetic unit hydrograph (Fig.16.1). This method may be applied in the catchment having area between 25 to 25000 km^2 and is based on three parameters namely base width (T), peak discharge (Q_p), and lag time (basin lag, t_p). The following are the empirical formula involving the three parameters:
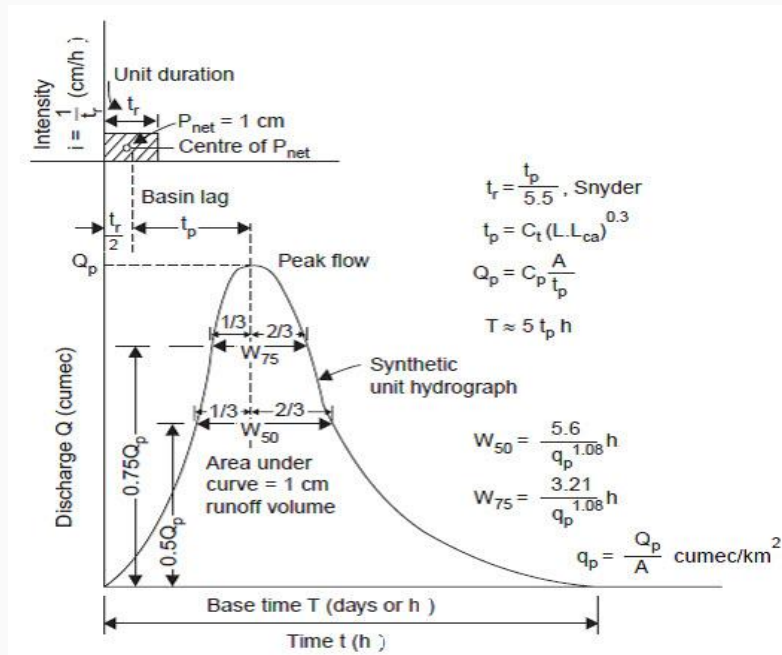
Fig. 16.1. Synthetic unit hydrograph parameters. (Image sources: Raghunath. H.M., 2006)

Lag time, $\qquad t_p = C_t \, (L \, L_{ca})^{0.3}$ $\qquad\qquad$ (16.1)

Standard duration of net rain, $\quad t_r = t_p \, /5.5$ $\qquad\qquad$ (16.2)

For this standard duration of net rain,

Peak flow, $\qquad\qquad Q_p = C_p \, A/t_p$ $\qquad\qquad$ (16.3)

Time base in days, $\qquad\qquad T = 3+3(t_p/24)$ $\qquad\qquad$ (16.4)

Peak flow per km^2 of basin, $\quad q_p = Q_p \, /t_p$ $\qquad\qquad$ (16.5)

Snyder subsequently proposed an expression to allow for some variation in the basin lag with variation in the net rain duration, i.e., if the actual duration of the storm is not equal to t_r given by Eq. (16.2) but is t_r', then

$$t_{pr} = t_p + (t_r' - t_r \, /4) \qquad\qquad (16.6)$$

Where,

t_{pr} = basin lag for a storm duration of t_r', and t_{pr} is used instead of t_p in Eq. (16.3), (16.4), (16.5).

In the above equations,

t_p = lag time (basin lag), h

C_t , C_p = empirical constants (C_t = 0.2 to 2.2, C_p =2 to 6.5, the value depending on the basin characteristics and units)

A = area of the catchment (km^2)

L = length of the longest water course, that is of the main stream from the gauging stations (outlet or measuring point) to its upstream boundary limit of the basins, (km) (Fig 16.2)

L_{ca} = length along the main stream from the gauging station (outlet) to a point on the stream opposite the areal center of gravity (centroid) of the basin
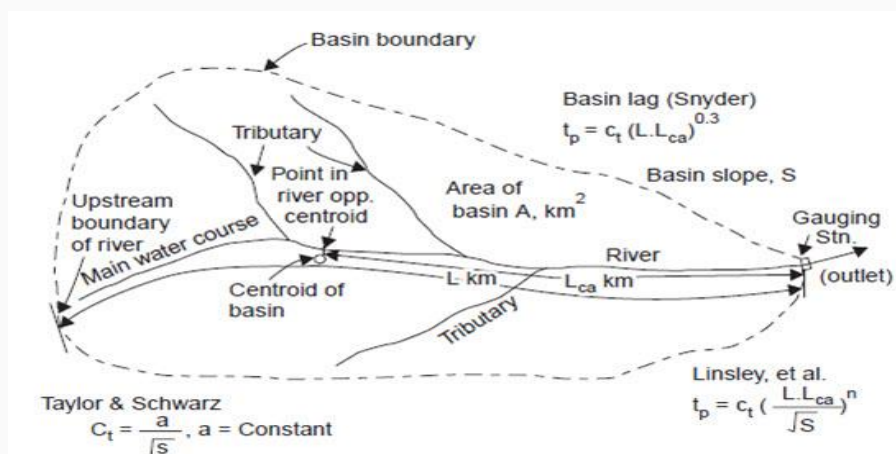
Fig. 16.2. Basin characteristics (Snyder). (Sources: Raghunath, 2006)

As specified by Snyder, the shape of the unit hydrograph is likely to be affected by the basin characteristics like area, topography, shape, slope, drainage density and channel storage. The size and shape of the basin is determined by measuring the length of the main stream channel. The coefficient C_t reflects the size, shape and slope of the basin.

Linsley et al. (1975), gave an expression for the lag time in terms of the basin characteristics as

$$t_p = C_t (LL_{ca}/S^{0.5})^n \tag{16.7}$$

Where, S = basin slope, and the values of n and C_t, when L, L_{ca} were measured in miles are n = 0.38

C_t = 1.2, for mountainous region

= 0.72, for foot hill areas

= 0.35, for valley areas

Taylor and Scwarz found from an analysis (when L and L_{ca} measured in miles) that

$$C_t = 0.6/S^{0.5} \tag{16.8}$$

Time base in h, $\qquad\qquad T = 5(t_{pr} + t_r/2) \tag{16.9}$

For developing a synthetic unit hydrograph for a basin for which the stream flow records are not available is to collect the data for the basin like A, L, L_{ca} and to get the coefficients, C_t and C_p from adjacent basins whose streams are gauged and which are hydro meteorologically homogeneous. The three parameters, i.e., the time to peak, the peak flow and the time base are determined from the Snyder's empirical equations, and the unit hydrograph can be sketched so that the area under the curve is equal to a runoff volume of 1 cm. Empirical formulae have been developed by the US Army Corps of Engineers (1959) for the widths of W_{50} and W_{75} of the hydrograph in hours at 50% and 75% height of the peak flow ordinate, respectively, (see Fig. 16.3) as

$$W_{50} = 5.6/q_p^{1.08} \tag{16.10}$$

$$W_{75} = W_{50}/1.75 \tag{16.11}$$

A still better shape of the unit hydrograph can be sketched with these widths (Fig. 16.1). The base time T given by Eq. (16.4) gives a minimum of 3 days even for very small basins and is in much excess of delay attributable to channel storage. In such cases, the author feels T given by Eq. (16.4) be adopted and the unit hydrograph sketched such that the area under the curve gives a runoff volume of 1 cm.
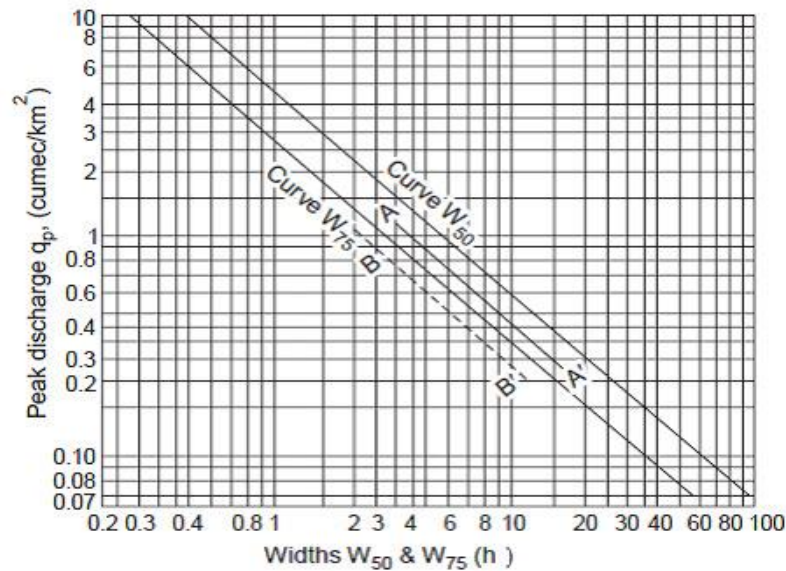
Fig.16.3. Width W$_{50}$ and W$_{75}$ for synthetic UG (US Army, 1959). (Sources: Raghunath, 2006)

16.2 Instantaneous Unit Hydrograph

The difficulty of using a unit hydrograph of a known duration has been overcome by the development of the instantaneous unit hydrograph (IUH). The IUH is a hydrograph of runoff resulting from the instantaneous application of 1 cm net rain on the watershed. The IUH in conjunction with the design storm can be used to obtain the design flood by using a convolution integral. The IUH was first proposed by Clark in 1945. The IUH can be developed either directly from the observed data or by adopting conceptual models.

Determination of IUH by S- Curve Hydrograph

In Fig. 16.4, S_t is the S-curve ordinate at any time t (due to t_r-h UG) and S'_t is the ordinate at time t of the S-curve lagged by t'_r-h, then the t'_r-h UGO at time t can be expressed as

$$U(t_r', t) = (S_t - S_t') \, t_r / t_r' \qquad (16.12)$$
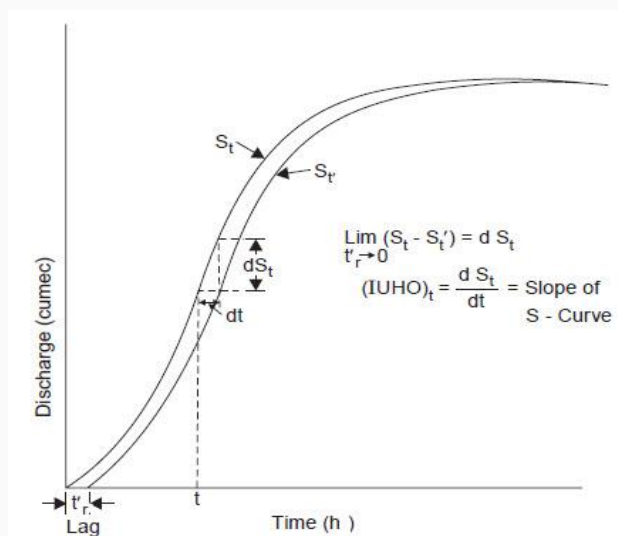
Fig. 16.4. IUH as S-curve derivative. (Sources: Raghunath. H.M., 2006)

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As t'_r progressively diminishes, i.e., $t'r \rightarrow 0$, Eq. (16.12) reduces to the form (as can be seen from Fig. 16.4)

$$U(0, t) = dS_t/dt \qquad (16.13)$$

i.e., the ordinate of the IUH at any time t is simply given by the slope of the S-curve at time t; in other words, the S-curve is an integral curve of the IUH. Since the S-curve derived from the observed rainfall-runoff data cannot be too exact, the IUH derived from the S-curve is only approximate. The IUH reflects all the catchment characteristics such as length, shape, slope, etc., independent of the duration of rainfall, thereby eliminating one variable in hydrograph analysis. Hence, it is useful for theoretical investigations on the rainfall-runoff relationships of drainage basins. The determination of the IUH is analytically more tedious than that of UG but it can be simplified by using electronic computers.

The t'_r-UGO can be obtained by dividing the IUH into t'_r-hr time intervals, the average of the ordinates at the beginning and end of each interval being plotted at the end of the interval (Fig. 16.5).
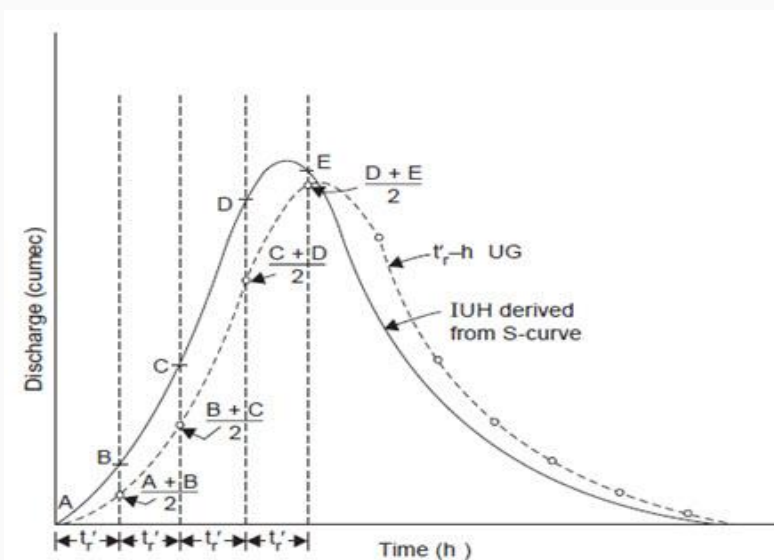
Fig. 16.5. t_r/- hr UG derived from IUH. (Sources: Raghunath. H.M., 2006)

Module 3: Soil Erosion Processes and Estimation

Lesson 17 Estimation of Soil Erosion

17.1 Introduction

The Universal Soil Loss Equation (USLE), developed by Agricultural Research Service (ARS) scientists W. Wischmeier and D. Smith, has been the most widely accepted and utilized soil loss equation for over 30 years. Designed as a method to predict average annual soil loss caused by sheet and rill erosion, the USLE is often criticized for its lack of applications. While it can estimate long - term annual soil loss and guide conservationists on proper cropping, management, and conservation practices, it cannot be applied to a specific year or a specific storm. The USLE is a mature technology and enhancements to it are limited due to its simple equation structure.

17.2 The Universal Soil Loss Equation (USLE)

The USLE developed in the USA is the most widely used empirical model worldwide for estimating soil loss (Wischmeier and Smith, 1965). Information from the USLE is used in planning and designing conservation practices. This model is not strictly based on hydraulic principles and soil erosion theory. It makes simplified assumptions in the processes of soil erosion. The USLE was specifically intended to predict soil loss from cultivated soils under specific characteristics. It has sometimes been used inappropriately and applied to soil and land use conditions different from those for which it was developed. It provides a long-term annual average estimate of soil loss from small plots or field segments with defined dimensions. The USLE was developed from measured data rather than using physically-based modeling approaches.

The limited consideration of all the complex and interactive factors and processes of soil erosion with the USLE limits its applicability to all conditions.

The USLE is, however, advantageous over sophisticated models because it is simple, easy to use, and does not require numerous input parameters or extensive data sets for prediction. The simplicity of the equation for its practical use has sacrificed accounting for all the details of soil erosion. Parameters are estimated from simple graphs and equations. Unlike process-based models, the USLE cannot simulate the following:

- Runoff, nutrient, and soil loss from watersheds or large catchment areas.

- Soil loss on an event or daily basis and variability of soil loss from storm to storm.

- Interrill, rill, gully, and streambank erosion separately.

- Processes of concentrated flow or flow channelization and sediment deposition.

- Detailed processes (e.g., detachment, transport, and deposition).

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The average annual soil loss is estimated as:

A= R*K*LS*C*P

Where, A is average annual soil loss (Mg ha^{-1}), R is rainfall and runoff erosivity index for the location of interest, K is erodibility factor, LS is topographic factor, C is cover and management factor, and P is support practice factor. The early versions of USLE were exclusively solved using tables and figures (e.g. nomographs). The continued improvement has resulted in MUSLE and Revised USLE (RUSLE 1and 2).

- **Rainfall and Runoff Erosivity Index (EI)**

The EI is computed as the product of total storm energy (E, J/m^2) times the maximum 30-min intensity (I_{30}) of the rain (mm h^{-1}).

EI = E × I_{30}

The USLE uses the annual EI which is computed by adding the EI values from individual storms that occurred during the year. According to Wischmeier and Smith (1978), the EI corresponds closely to the amount of soil loss from a field. The EI as used in the USLE over-estimates the EI for tropical regions with intensive rains. The USLE-computed EI is only valid for rain intensities ≤ 63.5mm h^{-1}. Modifications to EI have been proposed for tropical regions (Lal, 1976). The 30-minute intensity for a given storm and location is obtained from rain gauge charts recording the rainfall. Values of EI_{30} below 50 **(**mm h^{-1}**)** correspond to dry regions and those above 500 (mm h^{-1}) correspond to humid regions.

- **Rainfall Erosivity factor (R)**

The erosivity factor of rainfall (R) is a function of the falling raindrops and the rainfall intensity, Wischmeier and Smith (1958) found that the product of the kinetic energy (E, j/m^2) of the raindrop and the maximum intensity of rainfall over a duration of 30 minutes (I_{30}) of the rain (mm h^{-1}), in a storm, was the best estimator of soil loss. This product is known as EI value.

EI = E × I_{30} (17.2)

The USLE uses the annual EI which is computed by adding the EI values from individual storms that occurred during the year. According to Wischmeier and Smith (1978), the EI corresponds closely to the amount of soil loss from a field. The EI as used in the USLE over-estimates the EI for tropical regions with intensive rains. The USLE-computed EI is only valid for rain intensities ≤ 63.5mm h^{-1}. Modifications to EI have been proposed for tropical regions (Lal, 1976). The 30-minute intensity for a given storm and location is obtained from rain gauge charts recording the rainfall. Values of EI30 below 50 **(**mm h^{-1}**)** correspond to dry regions and those above 500 (mm h^{-1}) correspond to humid regions.

Soil Erodibility Factor (K)

Soil erodibility refers to soil's susceptibility to erosion. It is affected by the inherent soil properties. The K values for the development of USLE were obtained by direct measurements

of soil erosion from fallow and row-crop plots across a number of sites in the USA primarily under simulated rainfall. The K values are now typically obtained from a nomograph or the following equation:

K = [0.00021 × M1.14 × (12 − a) + 3.25 × (b − 2) + 3.3 × 10−3(c − 3)] /100

M = (% silt + % very fine sand) × (100 − % clay)

Where, M is particle-size parameter, a is % of soil organic matter content, b is soil structure code (1 = very fine granular; 2 = fine granular; 3 = medium or coarse granular; 4 = blocky, platy, or massive), and c profile permeability (saturat d hydraulic conductivity) class [1 = rapid (150 mm h−1); 2 = moderate to rapid (50–150 mm h−1); 3 = moderate (12–50 mm h−1); 4 = slow to moderate (5–15 mm h−1); 5 = slow (1–5 mm h−1); 6 = very slow (<1 mm h−1)]. The size of soil particles for very fine sand fraction ranges between 0.05 and 0.10 mm, for silt content between 0.002 and 0.05, and clay <0.002 mm. The soil organic matter content is computed as the product of percent organic C and value given in Table 17.1.

Table 17.1. K Factor Data (Organic Matter Content)

Textural Class	Average	Less than 2 %	More than 2 %
Clay	0.22	0.24	0.21
Clay Loam	0.30	0.33	0.28
Coarse Sandy Loam	0.07	--	0.07
Fine Sand	0.08	0.09	0.06
Fine Sandy Loam	0.18	0.22	0.17
Heavy Clay	0.17	0.19	0.15
Loam	0.30	0.34	0.26
Loamy Fine Sand	0.11	0.15	0.09
Loamy Sand	0.04	0.05	0.04
Loamy Very Fine Sand	0.39	0.44	0.25
Sand	0.02	0.03	0.01
Sandy Clay Loam	0.20	-	0.20
Sandy Loam	0.13	0.14	0.12
Silt Loam	0.38	0.41	0.37
Silty Clay	0.26	0.27	0.26

Silty Clay Loam	0.32	0.35	0.30
Very Fine Sand	0.43	0.46	0.37
Very Fine Sandy Loam	0.35	0.41	0.33

(Source: http://www.omafra.gov.on.ca/english/engineer/facts/00-001.htm#background)

- **Topographic Factor (LS)**

The USLE computes the LS factor as a ratio of soil loss from a soil of interest to

that from a standard USLE plot of 22.1m in length with 9% slope as follows:

LS = $(\text{Length}/22.1)^m$ $(65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065)$

m = 0.6 $(1 - \exp(-35.835 \times S))$

$\theta = \tan^{-1}(S/100)$

Where, S is field slope (%) and θ is field slope steepness in degrees.

Table 17.2. LS Factor Calculation

Slope Length ft (m)	Slope (%)	LS Factor
100 ft (31 m)	10	1.3800
	8	0.9964
	6	0.6742
	5	0.5362
	4	0.4004
	3	0.2965
	2	0.2008
	1	0.1290
	0	0.0693
200 ft (61 m)	10	1.9517
	8	1.4092
	6	0.9535
	5	0.7582

	4	0.5283
	3	0.3912
	2	0.2473
	1	0.1588
	0	0.0796
400 ft (122 m)	10	2.7602
	8	1.9928
	6	1.3484
	5	1.0723
	4	0.6971
	3	0.5162
	2	0.3044
	1	0.1955
	0	0.0915
800 ft (244 m)	10	3.9035
	8	2.8183
	6	1.9070
	5	1.5165
	4	0.9198
	3	0.6811
	2	0.3748
	1	0.2407
	0	0.1051
1600 ft (488 m)	10	5.5203
	8	3.9857
	6	2.6969
	5	2.1446

	4	1.2137
	3	0.8987
	2	0.4614
	1	0.2964
	0	0.1207
3200 ft (975 m)	10	7.8069
	8	5.6366
	6	3.8140
	5	3.0330
	4	1.6015
	3	1.1858
	2	0.5680
	1	0.3649
	0	0.1386

(Source: http://www.omafra.gov.on.ca/english/engineer/facts/12-051.htm)

- **Cover-Management Factor (C)**

The C-factor is based on the concept that soil loss changes in response to the vegetative crop cover during the five crop stage periods: rough fallow, seedling, establishment, growing, and maturing crop, and residue or stubble. It is computed as the soil loss ratio from a field under a given crop stage period compared to the loss from a field under continuous and bare fallow conditions with up- and down-slope tillage (Wischmeier and Smith, 1978). Depending on the crop type and tillage method, the two sub-factors defining the C, are multiplied to compute the C-values. Estimates of C values for selected vegetation types are shown in Table 17.4. Detailed calculations of C values are presented by Wischmeier and Smith (1978).

- **Support Practice Factor (P)**

The P-factor refers to the practices that are used to control erosion. It is defined as the ratio of soil lost from a field with support practices to that lost from a field under up-and down-slope tillage without these practices. The P values vary from 0 to 1 where the highest values correspond to a bare without any support practices. Maintaining living and dead vegetative cover and practicing conservation tillage significantly reduces soil erosion. The combined use of various practices is more effective than a single practice for controlling erosion in highly erodible soils. In such a case, support practices (P) including contouring, contour strip-

cropping, terracing, and grass waterways must be used. The P values are obtained from Tables 17.4 and 17.5.

In systems with various support practices, P values are calculated as follows:

P = Pc × Ps × Pt

where Pc is contouring factor for a given field slope, Ps is strip cropping factor, and Pt is terrace sedimentation factor (Table 17.5).

Table 17.3. "C" values for some tillage and cropping systems

Vegetation	Description	C values
Grain corn	Moldboard plow, no residues, plowed during:	
	– fall	0.40
	– spring	0.36
	Mulch tillage	0.24
	Chisel plow, >50% residue cover, spring plowing	0.20
	Ridge tillage	0.14
	No-till with 100% residue cover	0.05
Corn silage and beans	Moldboard plow, no residues, plowed during:	
	– fall	0.50
	– spring	0.45
	Mulch tillage	0.30
	Ridge tillage	0.17
	No-till with 100% residue cover	0.10
Cereals	Fall plowed	0.35
	Spring plowed	0.32
	Mulch tillage	0.21
	Ridge tillage	0.12
	No-till with 100% residue cover	0.08
Corn-soybean rotation	Moldboard plow, no residues, fall plowing	0.50
	Chisel plow, >50% residue cover, spring plowing	0.23
	No-till with 100% residue cover	0.05
Corn-soybean rotation	Moldboard plow, no residues, fall plowing	0.20
	Chisel plow, >50% residue cover, spring plowing	0.14
	No-till with 100% residue cover	0.05
Hay and pasture	Dense stand of sod-like grass	0.02
Forest	>90% canopy cover and 100% litter cover	0.001
Short and managed trees without understory vegetation (fruit trees)	At least 75% of canopy cover without litter cover	0.35
	At least 75% of canopy cover with about 30% litter cover	0.08

(Source: Humberto and Lal, 2008)

Table 17.4. P values for contouring and strip-cropping

Land slope (%)	Contouring		Strip cropping				
	P value	Maximum slope length (m)	P value			Strip width (m)	Maximum slope length (m)
			A	B	C		
1–2	0.60	122	0.3	0.45	0.60	40	243
3–5	0.50	91	0.25	0.38	0.50	30	182
6–8	0.50	61	0.25	0.38	0.50	30	122
9–12	0.60	36	0.30	0.45	0.60	24	74
13–16	0.70	24	0.35	0.52	0.70	24	49
17–20	0.80	18	0.40	0.60	0.80	18	36
20–25	0.9	15	0.45	0.68	0.90	15	30

(Source: Humberto and Lal, 2008)

Table 17.5. P values for combined support practices

Land slope (%)	Contour factor	Strip crop factor	Terrace factor		
			Terrace interval (m)	Closed outlets	Open outlets
1–2	0.60	0.30	33	0.5	0.7
3–8	0.50	0.25	33–44	0.6	0.8
9–12	0.60	0.30	43–54	0.7	0.8
13–16	0.70	0.35	55–68	0.8	0.9
17–20	0.80	0.40	69–60	0.9	0.9
21–25	0.90	0.45	90	1.0	1.0

(Source: Humberto and Lal, 2008)

Table 17.6. Management Strategies to Reduce Soil Losses

Factor	Management Strategies	Example
R	The R Factor for a field cannot be altered.	--
K	The K Factor for a field cannot be altered.	--
LS	Terraces may be constructed to reduce the slope length resulting in lower soil losses.	Terracing requires additional investment and will cause some inconvenience in farming. Investigate other soil conservation practices first.
C	The selection of crop types and tillage methods that result in the lowest possible C factor will result in less soil erosion.	Consider cropping systems that will provide maximum protection to the soil. Use minimum tillage systems where possible.
P	The selection of a support practice that has the lowest possible factor associated with it will result in lower soil losses.	Use support practices such as cross slope farming that will cause sediment deposition close to the source.

(Source: http://www.omafra.gov.on.ca/english/engineer/facts/05-067.htm)

17. 3 Application of USLE

1. The USLE was developed as a working tool for soil erosion prediction and soil conservation and erosion control planning. It was developed for application on very small land areas e.g. single fields within a farm, and most of the quantification of the factors in the equation were developed from studies on small field plots.

2. Application of the USLE to the analysis of nonpoint source pollution has been increasing in recent years and in many cases may be used beyond its limitations. Better predictive tools are needed, particularly with respect to sediment delivery ratios, and models which consider the physical processes involved in erosion and sediment transport.

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3. The USLE only predicts soil loss by sheet and rill erosion as a result of rainfall impact on soils. The movement of dislodged soil particles to streams is not modelled. In some applications of the USLE, this is covered by a sediment delivery ratio (S_d). The determination and use of sediment delivery ratios is subject to considerable controversy and misuse.

17.4 Limitations of USLE

1. The model applies only to sheet erosion since the source of energy is rain; so it never applies to linear or mass erosion and predicts the average soil loss.

2. The type of countryside: the model has been tested and verified in plain and hilly countries with 1-20% slopes, and excludes young mountains, especially slopes steeper than 40%, where runoff is a greater source of energy than rain and where there are significant mass movements of earth.

3. The type of rainfall: the relations between kinetic energy and rainfall intensity generally used in this model apply only to the American Great Plains, and not to mountainous regions although different sub-models can be developed for the index of rainfall erosivity, R.

4. The model applies only for average data over 20 years and is not valid for individual storms. A MUSLE model has been developed for estimating the sediment load produced by each storm, which takes into account not only rainfall erosivity but also the volume of runoff (Williams 1975).

5. Lastly, a major limitation of the model is that it neglects certain interactions between factors in order to distinguish more easily the individual effect of each factor. For example, it does not take into account the effect on erosion of slope combined with plant cover, or the effect of soil type along with the effect of slope.

6. The USLE does not calculate sediment deposition.

Lesson 18 Modification of Universal Soil Loss Equation

18.1 Introduction

Soil erosion is an important term for consideration in the planning of watershed development works. It reduces not only the storage capacity of the downstream reservoirs but also deteriorates the productivity of the watershed due to the loss of fertile top soil. Accurate estimation of sediment-transport rates depends on an accurate a priori estimation of overland flows.

It is necessary to quantify soil erosion more extensively, with the aim of providing a tool for planning soil conservation strategies on watershed basis. The formulation of proper watershed management programs for sustainable development requires information on watershed sediment yield. Prediction of the sediment yield is difficult to measure because of the complexity of the variables involved in erosion modeling. The universal soil loss equation (USLE), the revised version of it (RUSLE), and its modified version (MUSLE) are used in hydrology for computing the amount of potential soil erosion and sediment yield.

The USLE (Wischmeier and Smith, 1978) was developed for estimation of the annual soil loss from small plots of an average length of 22 m. Its application for individual storm events and large areas leads to large errors. However, its accuracy increases if it is coupled with a hydrological rainfall-excess model (Novotny and Olem, 1994). In the USLE model, there is no direct consideration of runoff, although erosion depends on sediment being discharged with flow and varies with runoff and sediment concentration. It has been observed that delivery ratios to determine sediment yield from soil loss equation can be used to predict accurately but it varies considerably. The reason for this may be due to the variation in rainfall distribution over time from year to year.

18.2 Modified USLE

Williams (1975) modified the USLE to estimate sediment yield for a single runoff event. On the basis of that runoff is a superior indicator of sediment yield than rainfall; i.e., no runoff yields no sediment, and there can be rainfall with little or no runoff-Williams (1975) replaced the R (rainfall erosivity) factor with a runoff factor. His analysis revealed that using the product of volume of runoff and peak discharge for an event yielded more accurate sediment yield predictions, especially for large events, than the USLE with the R factor. The Modified USLE, or MUSLE, is given by the following (Williams, 1975):

$S = 11.8 (Q \times q_p \times A)^{0.56} \times K \times C \times P \times LS \times CFRG$

Where,

S = Sediment yield for a single event in (Mg),

Q = Total event runoff volume (m^3),

q_P = Event peak discharge ($m^3 s^{-1}$),

A = Area of the hydrologic response unit (HRU) (ha) and

K, LS, C, and P = USLE parameters and these are dimensionless.

CFRG = Coarse fragment factor, which is estimated as

CFRG = exp ($-0.053 \times$ Rock)

Where, Rock is % rock in the uppermost soil layer.

The MUSLE approach has been used to estimate sediment yield at various sites. Some errors, however, have been associated with both USLE and runoff model estimates, resulting in under- and over-prediction of sediment yield from various rainfall events and site-specific characteristics, and have led to various proposals to increase accuracy after regression analysis. The complexity of watershed systems has forced modelers and users to develop modified, calibrated or revised versions of the MUSLE. Due to errors associated with the classic USLE, especially those relating to topographic factors in terms of limited availability of data on steep slope gradients; it is still unclear how the USLE can be applied to complex slopes beyond the range of the extended model. Application of the MUSLE has not been documented. The structure of the MUSLE model has inherited some limitations from classic USLE, especially those related to slope steepness (S factor).

18.3 Revised USLE

The science of predicting soil erosion and sediment delivery has continued to be refined to reflect the importance of different factors on soil erosion and runoff. The Revised Universal Soil Loss Equation (RUSLE) has improved the effects of soil roughness and the effects of local weather on the prediction of soil loss and sediment delivery. The importance of estimating erosion and sediment delivery has long been recognized to plan for minimizing the pollution by sediments as well as the chemicals carried with soil particles. The visual effects of erosion include rills and gullies and sediment blockages found in culverts or drainage ditches. A well planned and engineered erosion control and/or water management plan will alleviate many concerns about construction site erosion and potential pollution. RUSLE is a science-based tool that has been improved over the last several years. RUSLE is a computation method which is used for site evaluation and planning purposes and to aid in the decision process of selecting erosion control measures. It provides an estimate of the severity of erosion. It also provides numbers to substantiate the benefits of planned erosion control measures, such as the advantage of adding a diversion ditch or mulch. For example, a diversion may shorten the length of slope used in calculating a LS factor. Also, the application of mulch will break raindrop impact and reduce runoff. This section provides a method to calculate soil loss. Following the step-by-step procedure will provide estimated erosion in terms of mass per unit area per year, which can be converted to the more usable unit. [If an electronic version is preferred, RUSLE, the computer model, is available from the Natural Resources Conservation Service, United States Department of Agriculture. The recent version (RUSLE-2) was released for implementation in 2003]. Currently, there is no method to predict soil loss from concentrated flow areas and gullies.

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Soil losses on construction sites can be predicted by using the Revised Universal Soil Loss Equation (RUSLE). The equation is as follows:

For bare ground conditions of graded areas of construction sites

A = R*K*(LS)*C* P

Where:

A is the computed soil loss Mg ha^{-1} year^{-1}.

R is the rainfall value reflecting the energy factor multiplied by the intensity factor.

EI is the abbreviation for energy and intensity and is called the Erosion Index. The energy component is related to the size of the raindrops while the intensity is the maximum intensity for a 30-minute interval and is measured in inches per hour. EI is frequently illustrated in graphs by showing the percent of EI that occurs within a period of days or months. From the index, one can determine the period when the most intense storms are likely to occur.

Example 1: Using the given information, determine the sediment yield from a storm with a total runoff volume of 120 m³ and a peak discharge of 5 m³/s.

Solution:

K = 0.33

LS = 0.697

C = 0.004

P = 0.5

$(Q\, q_P)^{0.56} = (120 \times 5)^{0.56} = (600)^{0.56} = 36$

$S = 95\, (Q \times q_p)^{0.56} \times K \times C \times P \times LS = P95 \times 36 \times 0.33 \times 0.697 \times 0.004 \times 0.5 = 1.57$ Mg.

Table 18.1, 2,3, show list of the cover factor C values for planted cover crops for erosion control at construction sites.

Table 18.1. Cover Factor C Values for Different Growth Periods for Planted Cover Crops for Erosion Control at Construction Sites

	SB (seedbed preparation)	Period 1 (establishment)	Period 2 (development)	Period 3a (maturing crop)	Period 3b (maturing crop)	Period 3c (maturing crop)
Crop Canopy[1]	0-10%	10-50%	50-75%	75-80%	75-90%	75-96%
Seeding is on topsoil, without a mulch	0.79	0.62	0.42	0.17	0.11	0.06
Seeding is on a desurfaced area, where residual effects of prior vegetation are no longer significant	1.0	0.75	0.50	0.17	0.11	0.06
sod	0.01	0.01	0.01	0.01	0.01	0.01

[1] Percent canopy cover is the percentage of the land surface that would not be hit by directly falling rain drops because the drops would be intercepted by the plant. It is the portion of the soil surface that would be covered by shadows if the sun were directly overhead.

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(Source: http://www.cdrpc.org/NET/WQ/ErosANDsed/3rusle.pdf)

Table 18.2. Cover Factor C value for Established Plants

	Percent Cover[1]	Plant Type	Percentage of surface covered by residue in contact with the soil					
			0%	20	40	60	80	95+
C factor for grass, grasslike plants, or decaying compacted plant litter	0	Grass	0.45	0.20	0.10	0.042	0.013	0.0003
C factor for broadleaf herbaceous plants (including most weeds with little lateral root networks), or un-decayed residues	0	Weeds	0.45	0.24	0.15	0.091	0.043	0.011
Tall weeds or short brush with average drop height[2] of =20 inches	25	Grass	0.36	0.17	0.09	0.038	0.013	0.003
		Weeds	0.36	0.20	0.13	0.083	0.041	0.011
	50	Grass	0.26	0.13	0.07	0.035	0.012	0.003
		Weeds	0.26	0.16	0.11	0.076	0.039	0.011
	75	Grass	0.17	0.12	0.09	0.068	0.038	0.011
		Weeds	0.17	0.12	0.09	0.068	0.038	0.011
Mechanically prepared sites, with no live vegetation and no topsoil, and no litter mixed in.	0	None	0.94	0.44	0.30	0.20	0.10	Not given

[1] Percent cover is the portion of the total area surface that would be hidden from view by canopy if looking straight downward.
[2] Drop height is the average fall height of water drops falling from the canopy to the ground.

(Source: http://www.cdrpc.org/NET/WQ/ErosANDsed/3rusle.pdf)

Table 18.3 C factor value for different classes

Land use class	Average C factor
1. Primarily forest (canopy cover >40%)*	0.002
2. Secondary forest (canopy cover 10%—40%)**	0.006
3. Shrub*	0.014
4. Rice**	0.10
5. Orchard**	0.11
4. Upland**	0.377
5. Grazing land**	0.11

*Adapted from Wischmeier and Smith (1978), Renard et al., 1997; ** Calculation from Morgan (1995)

(Source: http://www.msu.edu/~xuhui3/index_c.html)

Table 18.4 lists P factors for surface conditions on construction sites in relation to bare soils.

Table 18.4 conservation practice factor (P)

Land use type	slope(%)	P factor
Agricultural land	0—5	0.11
	5—10	0.12
	10—20	0.14
	20—30	0.22
	30—50	0.31
	50—100	0.43
Other land	all	1.00

(Source: http://www.msu.edu/~xuhui3/index_c.html)

Example 2: In a 23 ha catchment, soil erosion is to be evaluated. The following information for the catchment is available. Calculate the soil loss.

R = 1000 (MJ-mm/ha) (mm/h) per year

K = 0.25 M/ha/R

LS = 0.1

Contour - farming in 13 ha (P = 0.6)

Strip cropping in 9 ha (P = 0.3)

Crops are maize and cowpea (assume weighted C= 0.5)

Solution:

$$\text{Weighted P} = \frac{(13 * 0.6) + (9 * 0.3)}{23} = \frac{7.8 + 2.7}{23} = 0.45$$

$$\text{Soil loss rate, A} = R\ K(LS)C\ P = 1000 * 0.25 * 0.1 * 0.5 * 0.45$$

$$= 5.625 \text{ Mg/ha/year}$$

Table 18.6. Summary of the differences between the USLE and RUSLE

Factor	Universal Soil Loss Equation (USLE)	Revised Universal Soil Loss Equation (RUSLE)
R	Based on long-term average rainfall conditions for specific geographic areas in the U.S.	Generally the same as USLE in the Eastern US. Values for Western States (Montana to New Mexico and west) are based on data from more weather stations and thus are more precise for any given location. RUSLE computes a correction to R to reflect the effect of raindrop impact for flat slopes striking water ponded on the surface.
K	Based on soil texture, organic-matter content, permeability, and other factors inherent to soil type.	Same as USLE but adjusted to account for seasonal changes such as freezing and thawing, soil moisture, and soil consolidation.
LS	Based on length and steepness of slope, regardless of land use.	Refines USLE by assigning new equations based on the ratio of rill to interrill erosion, and accommodates complex slopes.
C	Based on cropping sequence, surface residue, surface roughness, and canopy cover, with are weighted by the percentage of erosive rainfall during the six crop stages. Lumps these factors into a table of soil loss ratios, by crop and tillage scheme.	Uses the subfactors: prior land use, canopy cover, surface cover, surface roughness, and soil moisture. Refines USLE by dividing each year in the rotation into 15-day intervals, calculating the soil loss ratio for each period. Recalculates a new soil loss ratio every time a tillage operation changes one of the subfactors. RUSLE provides improved estimates of soil loss changes as they occur throughout the year, especially relating to surface and near-surface residue and the effects of climate on residue decomposition.
P	Based on installation of practices that slow runoff and thus reduce soil movement. P factor values change according to slope ranges with some distinction for various ridge heights.	P factor values are based on hydrologic soil groups, slope, row grade, ridge height, and the 10-year single storm erosion index value. RUSLE computes the effect of stripcropping based on the transport capacity of flow in dense strips relative to the amount of sediment reaching the strip. The P factor for conservation planning considers the amount and location of deposition.

(Source: http://ftp-fc.sc.egov.usda.gov/NCGC/products/nri/1997- 999nri/rusle.pdf)

18.4 Coupled SCS CN Method with USLE

The Soil Conservation Service curve number (SCS-CN) and Revised Universal Soil Loss Equation (RUSLE) models are widely used. A study incorporated antecedent moisture condition (AMC) in runoff production and initial abstraction of the SCS-CN model, and considered the direct effect of runoff on event soil loss by adopting a rainfall-runoff erosivity factor in the RUSLE model. The modified SCS-CN and RUSLE models were coupled to link rainfall-runoff-erosion modeling. The effects of AMC, slope gradient and initial abstraction ratio on curve number of SCS-CN, as well as those of vegetation cover on cover-management factor of RUSLE, were also considered. Three runoff plot groups covered by sparse young trees, native shrubs and dense tussock, respectively, were established in the Yang Juangou catchment of Loess Plateau. Rainfall, runoff and soil loss were monitored during the rainy season in 2008–2011 to test the applicability of the proposed approach. The original SCS-CN model significantly underestimated the event runoff, especially for the rainfall events that

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have large 5-day antecedent precipitation, whereas the modified SCS-CN model was accurate in predicting event runoff with Nash-Sutcliffe model efficiency (EF) over 0.85.

The SCS-CN method is based on the principle of the water balance and two fundamental assumptions (Mishra and Singh, 2002). The first assumption is that the ratio of direct runoff to potential maximum runoff is equal to the ratio of infiltration to potential maximum retention. The second assumption states that the initial abstraction is proportional to the potential maximum retention. The water balance equation and the two assumptions are expressed mathematically.

Lesson 19 Measurement of Runoff and Sediment

19.1 Introduction

Uncontrolled soil erosion and the consequent silt deposition over downstream areas impacts many aspects of the environment- loss of fertile top soil, water quality, water supply, flood control, river regulation, reservoir lifespan, blocked natural groundwater recharge areas, irrigation, navigation, fishing, tourism, etc. It has attracted increasing attention from the public and engineers in the field. In this section, the main problems and issues related to river and reservoir sedimentation has been described to help the reader understand them better.

19.1.1 Degree and Intensity of Soil Erosion

- **Soil loss tolerance**

An evaluation of the seriousness of soil erosion needs to take into account the quantum of soil a given specific site is losing currently and the maximum permissible soil loss. Soil loss tolerance is the maximum rate of annual soil erosion that will not adversely affect the crop productivity to be obtained economically. The soil formation rate is an important factor in determining soil loss tolerance. Under natural conditions, the formation of about one cm soil may take anywhere between 50 to 150 years, while it takes about 100 years under farming conditions. This is based on the assumption that the parent rock has already undergone some weathering process towards formation of soil. An estimate puts the renewal rate at 1.25 tons per hectare per year for unconsolidated parent material, and much less for consolidated material. The formation of the weathering surface layer on a base rock of granite requires 10,000 to 100,000 years, while a base rock of non-granite needs much more time (Margan, 1980). So slow is the process of weathering that a person in his life time will not see a piece of rock changed into a mass of soil.

- **Soil erosion intensity**

Soil erosion intensity means that under the action of natural agents and human activities, the soil is eroded due to denudation. The displacement per unit area and unit time is expressed by the soil erosion modulus. According to the Chinese Standard, erosion intensity is classified as given in Table 19.1

Table 19.1. Soil erosion intensity

Degree	Mean annual erosion modulus (t km^{-2} ha^{-1})	Mean lost thickness (mm ha^{-1})
Slight	< 500, 1250, 2500	< 0.37, 0.92, 1.85
Light	500, 1250, 2500-6250	0.37, 0.92, 1.85–4.7
Moderate	6250–12500	4.7–9.2
Intensive	12500–20000	9.2–14.7

| Utterly intensive | 20000–37500 | 14.7–27.7 |
| Severe | >37500 | >27.7 |

<div align="center">(Source: http://whycos.org/IMG/pdf/948_E.pdf)</div>

19.1.2 Sediment Yield in a Basin

Water erosion is the most important type of erosion caused due to impact of rain drops and due to the flow of runoff. Its further importance under a monsoon climate, as occurs over India, is due to the sharp showers and copious runoff that follows the rainfall. In the entire process of erosion and transport; soil erosion, soil loss and sediment yield in a basin are three different but closely related concepts. Sediment yield is defined as the total sediment outflow from a watershed or drainage basin, measurable at a cross-section of reference in a specified period of time (Piest and Miller, 1975). In the comprehensive planning of a medium or small watershed, if the gross erosion and sediment delivery ratio are known, the sediment yield can be predicted.

Sediment observations are important baseline information for the optimal use of the water resources, for the protection against harmful impacts of the sediment as well as for the protection of the water and the environment. For that reason various types of sediment data are needed.

<div align="center">**Table 19.2. An overview of necessary sediment observations**</div>

Torrents	Rivers	Reservoirs and lakes
• Bed load • Bed load potential • Transportcapacity (maximum bed load discharge) • Bed lod discharge during floods • Bed load discharge graph • Grain size distribution during flood events • Bed load discharge of floods of different size (recurrence intervals) • Suspended sediment • Suspended sediment concentration • Relation between water discharge and suspended sediment concentration • Suspended sediment discharge • Sediment features • Grain size distribution • Grain shape and petrography • Bulk density of accumulations	• Bed load • Bed load potential • Transportcapacity (maximum bed load discharge) • Bed lod discharge during floods • Bed load discharge graph • Grain size distribution at flood events • Bed load discharge of floods of different size (recurrence intervals) • Suspended sediment • Suspended sediment concentration • Relation between water discharge and suspended sediment concentration • Suspended sediment discharge • Sediment features • Grain size distribution (as function of place, time and water discharge) of moving and laying bed load and suspended sediment • Grain shape and petrography • Specific weight • Transported wood volume per flood event	• Sediment in-and output • Sediment load (to be determined in in-and outflowing rivers) • Bed load • Delta survey • Suspended sediments • Suspended sediment concentration (as function of time and space) • Turbidity profiles • Composition of suspended sediments (grain size distribution, organic/inorganic, chemical/mineralogical, clastic) • Features of adsorption • Sedimentation rate • Volume change by redeposition and diagenesis of sediments • Grain shape and petrography • Composition of suspended sediments (grain size distribution, organic/inorganic, chemical/ mineralogical, clastic) • Transported wood volume per time

<div align="center">(Source: http://www.irtces.org/zt/11isrs/paper/Manfred_Spreafico.pdf)</div>

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Sediment load may be classified as suspended load or bed load according to the mode of movement in the river. Suspended load is the sediment that moves in suspension in water under the influence of turbulence. Bed load is the part of sediment load that moves in almost continuous contact with the stream bed by saltation and traction. That is, by bouncing, sliding and rolling on or near the stream bed by the force of water. According to its origin, or source of supply, the total amount of sediment transported in rivers may be divided into two parts: wash load and bed material load. Wash load consists of fine particles, which refers generally to sediment size finer than 0.062 mm, and the amount depends mainly upon supply from the source area. The discharge of bed material is controlled by the transport capacity of the stream, which depends upon bed composition and the relevant hydraulic parameters. Wash load moves entirely in suspension, while the bed material load may move either as temporarily suspended load or as bed load. Suspended sediment load is easier to measure and is mostly used in estimating catchment soil loss, reservoir sedimentation, etc. Despite a large number of studies, the bed load movement mechanism is not well understood and is either neglected or some tentative value is assumed for estimating total sediment flow passed a section or from a watershed.

19.2 Sediment Sampler

Sediment samplers are used to collect sediment-laden water sample from a flowing water body (river, tributary, canal, etc.). The sample is subjected to laboratory analysis to determine mainly the sediment content and also the chemical, physical, toxicological and biological composition of sediment. Samplers are also used to collect scoops or cores of soil from a known silt deposition site (e.g., reservoir bottom, flood plain) to gather historical information. Choosing the most appropriate sampling device and technique depends on the:

1) Purpose of sampling;

2) Location of sediment; and

3) Characteristics of sediment.

Sample Types:
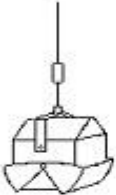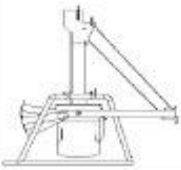
A description and rationale for the types of samples to be collected should be included in the plan. Different types of sampler are illustrated in Table 19.3 and Fig. 19.1.

- **Cores:** Vertical discrete grab samples. Most appropriate for historical contamination information or dredging decisions at heavily contaminated areas.

- **Cores:** Depth integrated composite samples. Most appropriate for reference and Section 404/401 issues.

- **Scoops and Dredges:** Surface (top two to four centimeters) sediment grab samples. Most appropriate for benthic, sediment oxygen demand (in-situ), recent ambient conditions and recent contaminant investigation.

- **Surface sediment composite samplers**: It may be used to reduce costs for specific conditions/situations such as some Section 404/401 issues or ambient or specific
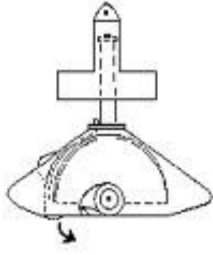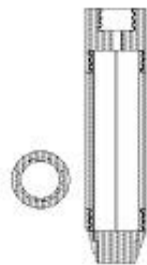
historical data. In general, however, discrete sampling is preferred if resources are available. An example of a discrete sample would be taking a section of one centimeter of sediment from a core sample that was originally one meter long.

Table 19.3. Table of Sediment Sampling Equipment

TYPE	MODEL	CURRENT	SUBSTRATE TYPE	REMARKS	ILLUSTRATION
GRAB	Spoon Scoop	Zero to Slight	All	• Use only in relatively calm and shallow water. • Relatively little sample disturbance. • Simple and inexpensive • Fines may washout when retrieved through water column	
GRAB	Eckman (Birge)	Zero to Very Slight	Clay and Silt	• Use in relatively calm water. • Pebbles and branches may interfere with jaw closure • Excellent jaw shape and cut. • Relatively little sample disturbance. • Poor stability. Light weight allows for tendency to "swim" in a current. Sometimes causes miss triggers. • 0.02 m² sample area. • Weight with sample is 10 kg.	
GRAB	Petite Ponar Peterson	Zero to Very Slight	Clay to fine gravel	• Need relatively calm/sheltered waters. • Good stability. • Poor jaw shape and cut. Sample disturbance. • Less washout if extra weights are used. • More cumbersome than an Eckman; requires a winch. • 0.1 - 0.2 m² sample area. • Weight with sample is 30 - 50 kg.	
CORE	Box	Zero to moderate	Clay to sand	• Difficult to handle. • Large sample size. • Requires boat/barge with winch. • Rectangular shaped box.	

(Source: http://www.epa.ohio.gov/portals/35/guidance/sedman2012.pdf)

TYPE	MODEL	CURRENT	SUBSTRATE TYPE	REMARKS	ILLUSTRATION
GRAB	Shipek	Zero to strong	Clay to gravel	• Requires boat/barge with winch (mini shipek can be used manually). • One of the most reliable in terms of triggering, stability, washout, and leaching. • Excellent jaw shape and cut. Extremely clean cutting action. • 0.04 m² sample area. • Weight with sample is 60 - 70 kg (mini shipek weight with sample is 20 - 30 kg).	
CORE	Manual	Zero to strong	Clay to sand. Inserts needed for sandy samples.	• Recommended for use in shallow water. • Deployed by hand or by driver (hammer). • Extension handles can be used for deeper waters.	
CORE	Coring Tubes	Zero to moderate	Clay to sand. Inserts needed for sandy samples.	• Quick and easy. • Relatively undisturbed sample. • Small sample volume. • Samples sometimes compressed.	
CORE	Split Spoon	Zero to moderate	Clay to sand. Inserts needed for sandy samples.	• Recommended for use in shallow water. • Deployed by hand or by driver (hammer). • Vertical profile remains intact and is visible. • Point design can reduce sample compaction. • Stones can interfere with collection. • Equipment is heavy.	

(Source: http://www.epa.ohio.gov/portals/35/guidance/sedman2012.pdf)

US DH-48   US DH-74

US DH-76
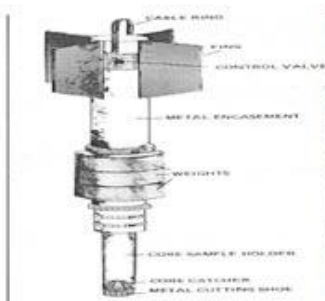
Gravity Corer   Ponar Sampler

**Fig. 19.1. Silt sampler. (Image
source: http://www.glc.org/tributary/documents/sedimentcourse/buffalo/D104Monitoring
ForSed_Zajd.pdf)**
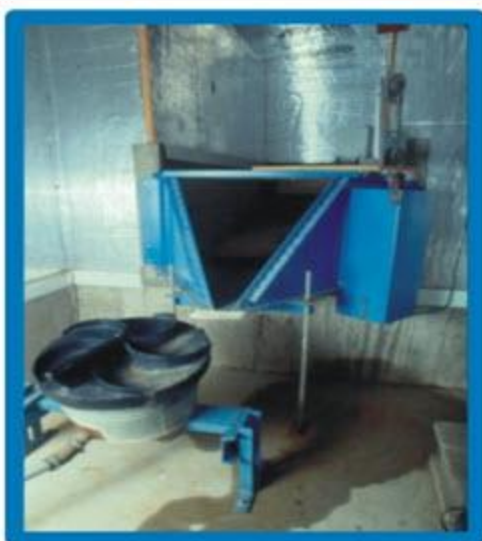
**Fig. 19.2 Coshocton wheel water sampler
(source: http://ars.usda.gov/Research/docs.htm?docid=10027)**

19.3 Discharge Proportionate Samplers

Flow measurement data are required for information on the rates, volumes and frequencies of waste discharges to the wastewater system. The measured trade waste volume is used together with sample analysis results to calculate the masses of pollutants discharged. The flow data gathered is used to:

• Determine mass (trade wastewater) and volume (sewer usage) charges accurately

• Determine a discharge factor

• Provide the customer with discharge data, so that they can manage their trade wastewater discharge more effectively

• Enable flow proportional sampling of the trade wastewater

• Provide hydraulic data to assess the future capacity of the wastewater system.

Different types of instrument used for measurement of flow velocity are illustrated in Figs. 19.3 to 19.7. Instruments for measurement of discharge like weirs and flumes are illustrated in Fig. 19.8 to 19.12.

Fig.19.3. Magnetic flow meter.
(Source: http://gallery.usgs.gov/images/07_20_2009/nsj7MYx43F_07_20_2009/large/000458-Current_Meter_(4).jpg)

Fig. 19.4. Current meter.
(Source: http://gallery.usgs.gov/images/07_20_2009/nsj7MYx43F_07_20_2009/large/000458-Current_Meter_(4).jpg)

Fig. 19.5. Horizontal float type recorder.
(Source: http://ecx.imagesamazon.com/images/I/61srCwKjQyL._AA1500_.jpg)
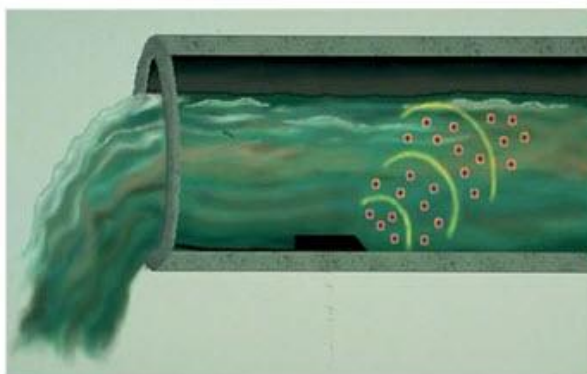
Fig. 19.6. Area velocity continuous wave Doppler (CWD).

Fig. 19.7. Area velocity sensor mounting hardware.

Fig. 19.8. Parshall flume.

Fig. 19.8. Replogle flume or long-throated flume. (Source: http://inmtn.com/images/flumes/bench-b-ramp-flume.jpg)

Fig. 19.9. Palmer BowlusFlume.
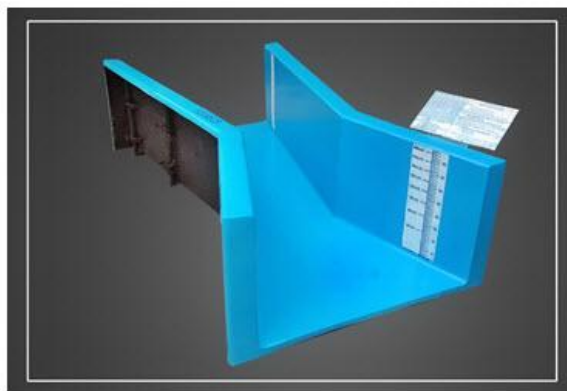
Fig. 19.10. Cut throat flume. (Source: http://www.niplastindia.com/Ni-Plast/cut-throat-flume-gallary.aspx)

Fig. 19.11. V-Notch Weir.

Fig. 19.12. Flow Metering Insert (Weir).

Water Level Measurement

These instruments are used to measure the depth of water level from the ground surface. The instruments are illustrated in Figures 19.13 to 19.16.

Fig. 19.13. Staff gauge. (Source; http://www.indiamart.com/sourcebusinesssyndicate/river-gauges.html)

Fig. 19.14. US type A-71 water level recorder. (Source: http://www.rickly.com/sm/Float-Type/WaterLevelRecorders.htm)
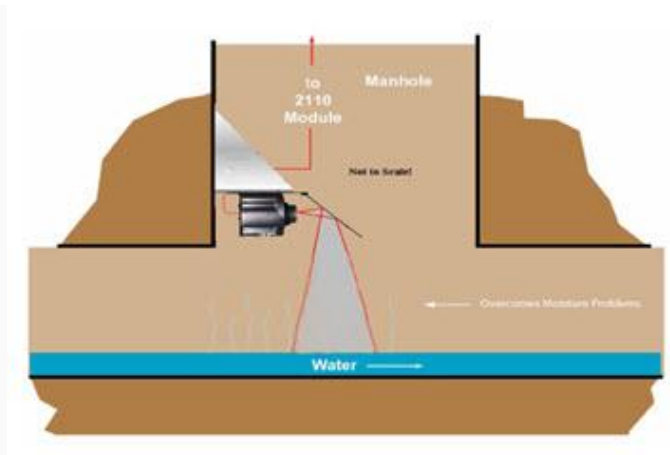
Fig. 19.15. Ultrasonic level measurement.

Fig. 19.16. Submerged probe / Pressure transducer. (Source: http://www.mi-wea.org/docs/Hummel%20 %20IPP%20Flow%20Paced%20Strategies.pdf)

Lesson 20 Models for Predicting Sediment Yield - I

20.1 Introduction

Modeling water and wind erosion is important, as it takes into consideration the effects of a larger number of causative factors on the erosion process than is otherwise possible. Modeling permits a better representation of the erosion process, which is helpful in predicting runoff and soil erosion rates, and identifying or choosing appropriate measures of erosion control. Modeling permits the:

(1) Understanding of the driving processes,

(2) Evaluation of on-site and off-site impacts on soil productivity and water and air pollution on large scale,

(3) Identification of strategies for erosion control, and

(4) Assessment of the performance of soil conservation practices for reducing water and wind erosion. Well-developed and properly calibrated models provide useful estimates of soil erosion risks.

Soil erosion results from a complex interaction of soil-plant-atmospheric forces, often supplemented by anthropogenic forces. Thus, modeling soil erosion requires a multidisciplinary approach among soil scientists, crop scientists, hydrologists, sedimentologists, meteorologists, social scientists and others, notably the engineers who device erosion controls measures and execute them. Models must be able to integrate processes, factors and causes at various spatial and temporal scales. Numerous models of differing prediction capabilities and utilities have been developed. The advent of technological tools such as remote sensing and GIS has significantly enhanced the usefulness of soil erosion models. The coupling of GIS and remote sensing with empirical and process-based soil erosion models has improved their predictive capability. The GIS stores the essential database needed as input or modeling erosion and elaboration of maps of erosion-affected areas. Remote sensing is useful to estimate land cover over large geographic areas, which is a critical input for modeling erosion. Remote sensing and GIS tools also allow the scaling up of modeled data from small plots (e.g., USLE) to large areas. Modeling soil erosion involves integration of complex and variable hydrological processes across large areas to understand the magnitude of soil erosion.

The model should be formulated conceptually, representing it by a flow chart. It is also a good test of the level of scientific understanding of the system and the degree to which the model is to be simplified because of insufficient knowledge. Different types of models for erosion estimation are given in Table 20.1.

Table 20.1 Types of models

Type	Description
Physical	Scaled-down hardware models usually built in the laboratory; need to assume dynamic similitude between model and real world.
Analogue	Use of mechanical or electrical systems analogous to system under investigation, e.g. flow of electricity used to simulate flow of water.
Digital	Based on use of digital computers to process vast quantities of data.
(a) Physically based	Based on mathematical equations to describe the processes involved in the model, taking account of the laws of conservation of mass and energy.
(b) Stochastic	Based on generating synthetic sequences of data from the statistical characteristics of existing sample data; useful for generating input sequences to physically based and empirical models where data are only available for short periods of observation.
(c) Empirical	Based on identifying statistically significant relationships between assumed important variables where a reasonable data base exists. Three types of analysis are recognized: (i) black-box, where only main inputs and outputs are studied; (ii) grey-box, where some detail of how the system works is known; (iii) white-box, where all details of how the system operates are known.

(Source: Morgan, 2005)

A model can be simplified by concentrating on those processes which have the greatest influence over the output and ignoring those which have very little effect. Once the processes operating within the model have been identified, they need to be described mathematically. The methods used can range from simple equations, often expressing a statistical relationship, to complex expressions related to the fundamental physics or mechanics of the process. The former are more common in empirical models, whereas the latter provide the foundation for physically based models.

It is generally recognized that a good model should satisfy the requirements of reliability, universal applicability, easy to use with a minimum of data, comprehensiveness in terms of the factors and erosion processes included and the ability to take account of changes in climate, land use and conservation practice. Unfortunately, many of the ideal characteristics of models conflict with each other. Ease of operation can mean that input data are readily available – for example from an accompanying user's manual. Such data, however, are at best only guide values and there may be uncertainty in how well they describe actual conditions.

- **Model Dimension**

(a)Three-Dimensional Model

Flow phenomena in natural rivers are three dimensional, especially those at or near a meander bend, local expansion and contraction, or a hydraulic structure. Sophisticated numerical schemes have been developed to solve truly three-dimensional flow phenomena. Three dimensional models need three-dimensional field data for testing and calibration. The

collection of such data is not only costly but also time consuming. Certain assumptions need to be made before a sediment transport formula developed for one-dimensional flows can be applied to a truly three-dimensional model. With the exception of detailed simulation of flow in an estuary area, secondary current, or flow near a hydraulic structure, truly three dimensional models are seldom used, and especially not for long-term simulations.

(b) Two-Dimensional Model

Two-dimensional models can be classified into two-dimensional vertically averaged and two dimensional horizontally averaged models. The former scheme is used where depth-averaged velocity or other hydraulic parameters can adequately describe the variation of hydraulic conditions across a channel. The latter scheme is used where width- or length-averaged hydraulic parameters can adequately describe the variation of hydraulic conditions in the vertical direction. Most two-dimensional sediment transport models are depth-averaged models.

(c) One-Dimensional Model

Most sediment transport models are one-dimensional, especially those used for long-term simulation of a long river reach. One dimensional model requires the least amount of field data for calibration and testing. The numerical solutions are more stable and require the least amount of computer time and capacity. However, one-dimensional models are not suitable for simulating truly two- or three-dimensional local phenomena.

(d) Semi-Two-Dimensional Model

A truly one-dimensional model cannot simulate the lateral variation of hydraulic and sediment conditions at a given river station. Engineers often take advantage of the non-uniform hydraulic and sediment conditions across a channel in their hydraulic design. For example, a water intake structure should be located on the concave side of a meandering bend, where the water is deep and sediment deposition is minimal. There are three types of semi-two dimensional models.

20.2 Empirical Models

Early examples of empirical models include those developed by:

a) Kornev and Kostyakov (1937)

$$W = a\, I^{0.75}\, L^{0.5}\, h^{1.5} \qquad\qquad (1)$$

Where,

W = washout (specific sediment yield); I = slope of ploughed lands;

L = slope length; h = water return rate; a = correction factor.

b) Glushkov and Polliakov (1946)

$$a = (S/\,10)\, I^{1/4} \qquad\qquad (2)$$

Where,

a = erosion coefficient; S = mean annual sediment concentration (g/m^3); I = channel slope.

c) Svetitsky (1962)

$$a_c = P_s / N^{1.22} \qquad\qquad (3)$$

Where,

a_c = erosion coefficients; P_s = mean annual sediment yield; N = energy characteristic.

Empirical models are developed mostly by relating experimentally generated or records of historical data through the use of coefficients and indices. A theoretical explanation of the empirical relations is generally not feasible.

20.3 SHETRAN Model

SHETRAN is a general, physically-based, spatially-distributed modeling system. It can be used to construct and run models of all or any part of the land phase of the hydrological cycle (including sediment and contaminant transport) for any geographical area. It is physically-based in the sense that the various flow and transport processes are modeled either by finite difference representations of the partial differential equations of mass, momentum and energy conservation, or by empirical equations derived from experimental research. The model parameters have a physical meaning and can be evaluated by measurement. Spatial distributions of basin properties, inputs and responses are represented on a three-dimensional, finite-difference mesh. The channel system is represented along the boundaries of the mesh grid squares as viewed in plan.

20.3.1 SHETRAN Hydrological Component

SHETRAN's hydrological component consists of subcomponents accounting for evapotranspiration and interception, overland and channel flow, subsurface flow, snowmelt and channel/surface aquifer exchange. The component is continually evolving as new process descriptions and solution schemes are introduced. Integration with the overland flow subcomponent allows overland flow to be generated both by an excess of rainfall over infiltration and by upward saturation of the soil column.

20.3.2 Processes Modeled by the SHETRAN Hydrological Component:

(1) Interception of rainfall on vegetation canopy (Rutter storage model)

(2) Evaporation of intercepted rainfall, ground surface water and channel water; transpiration of water drawn from the root zone (Penman-Monteith equation or the ratio of actual to potential evapotranspiration as a function of soil moisture tension)

(3) Snowpack development and snowmelt (temperature-based or energy budget methods)

(4) One-dimensional flow in the unsaturated zone (Richards equation)

(5) Two-dimensional flow in the saturated zone (Boussinesq equation)

(6) Two-dimensional overland flow; one-dimensional channel flow (Saint Venant equations)

(7) Saturated zone/channel interaction, including an allowance for an unsaturated zone below the channel

(8) Saturated zone/surface water interaction

Flow chart of the SHETRAN model is given below in Fig. 20.1.
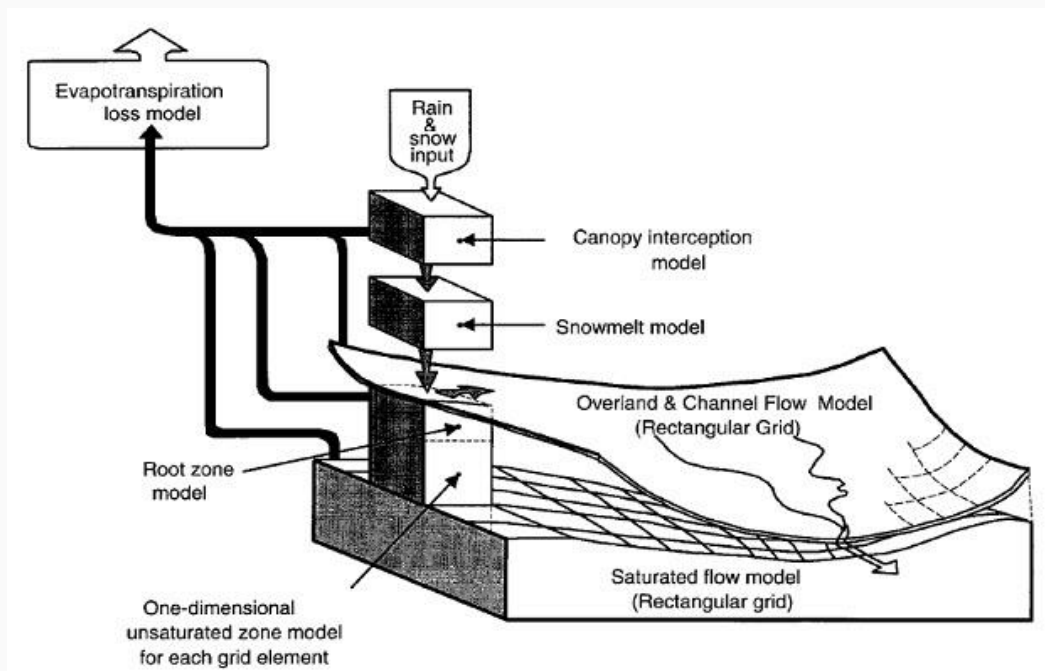
Fig. 20.1. Schematic diagram of the SHETRAN hydrological component.
(Source: http://unesdoc.unesco.org/images/0012/001278/127848e.pdf)

20.4 Ephemeral Gully Erosion Model (EGEM)

The EGEM was specifically developed to predict gully formation and erosion based on physical principles of gully bed and side-wall dynamics (Woodward, 1999; Foster and Lane, 1983). Common erosion models such as USLE, RUSLE, and WEPP do not include direct options for predicting gully erosion. The EGEM considers the dynamic processes of concentrated flow responsible for gully incision and head cut development. The EGEM is one of the few process-based models to predict gully erosion.

The EGEM consists of two major components (a) hydrology and (b) erosion. The hydrologic component is estimated using the runoff curve number, drainage area, watershed slope and flow depth, peak runoff discharge, and runoff volume. The erosion component is based on the width and depth of ephemeral channels. The EGEM can predict gully erosion for single storms or seasons or crop stage periods. It assumes that soil erodes to a depth of about 45 cm (e.g., tillage, resistant layer). The width of the gullies is computed using regression equations as:

Gulley and Ravine Control Structures

$W_e = 2.66 \, (Q^{0.396}) \, (n^{0.387}) \, S^{-0.16} CS^{-0.24}$

$W_u = 179 \, (Q^{0.552})(n^{0.556}) \, S^{0.199} CS^{-0.476}$

Where,

W_e is equilibrium channel width (m).

W_u is ultimate channel width (m).

Q is peak runoff rate ($m^3 \, s^{-1}$).

n is Manning's roughness coefficient.

S is concentrated runoff slope and CS is critical shear stress (Nm^{-2}). The detachment rate in gullies is computed similar to that in CREAMS by a modified form of rill erosion equation as follows:

$D = KC \, (1.35t - t_c)$

Where,

D is detachment rate ($g^{-2} \, s^{-1}$), KC is channel erodibility factor ($g \, s^{-1} \, N^{-1}$), t is average shear stress of flowing water (Nm^{-2}), and t_c is critical shear stress of soil (Nm^{-2})

20.5 EUROSEM Model

EUROSEM (Morgan et al. 1998) is an event-based model designed to compute the sediment transport, erosion and deposition over the land surface throughout a storm, schematic diagram of EUROSEM model is presented in Fig. 20.2. It can be applied to either individual fields or small catchments. Compared with other models, EUROSEM simulates Interrill erosion explicitly, including the transport of water and sediment from Interrill areas to rills, thereby allowing for deposition of material en route. This is considered more realistic than assigning all or a set proportion of the detached material to the rills. A more physically based approach to simulating the effect of vegetation or crop cover is used, taking into account the influence of leaf drainage. Soil conservation measures can be allowed by choosing appropriate values of the soil, micro topography and plant cover parameters so as to describe the conditions associated with each practice. Unlike other models, however, EUROSEM does not describe the eroded sediment in terms of its particle size. The flow chart of the EUROSEM model is given in Fig. 20.2.

Gulley and Ravine Control Structures
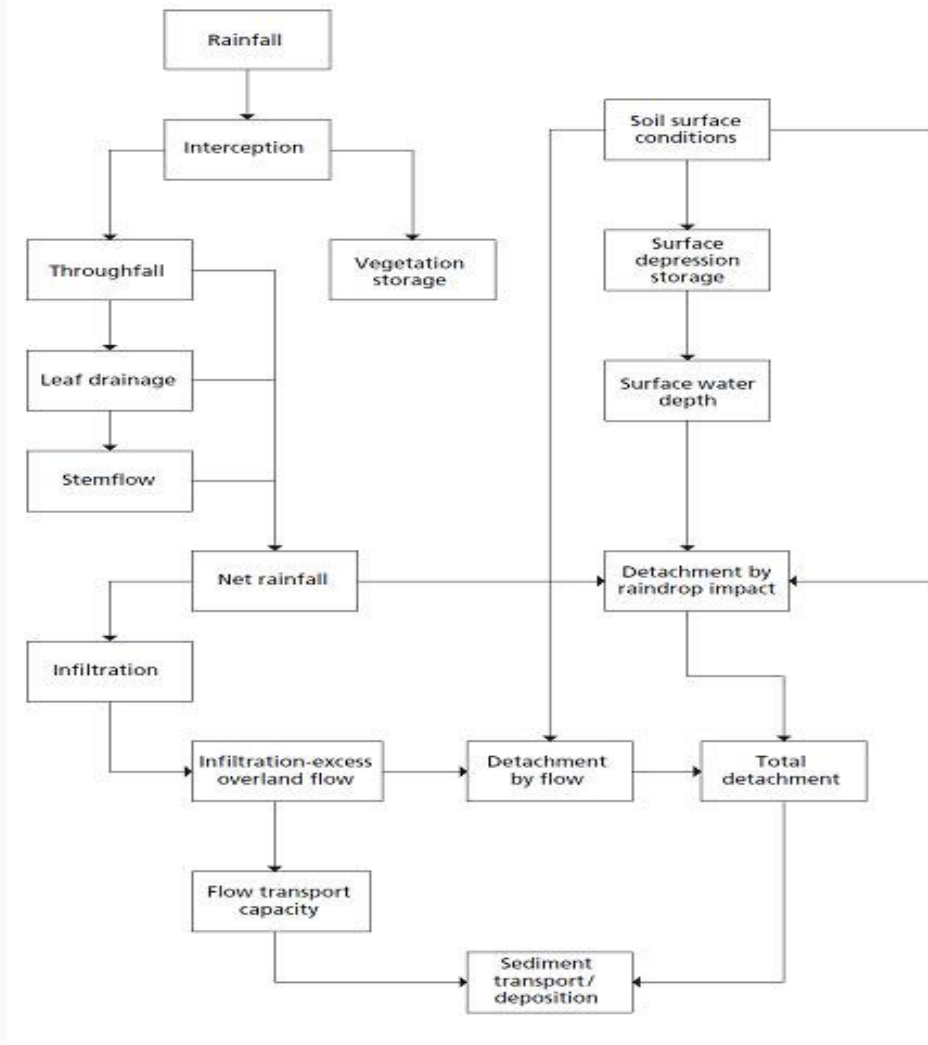
Fig. 20.2. Flow chart for the European Soil Erosion Model (EUROSEM). (Source: European Soil Erosion Model; Morgan et al. 1998;)

EUROSEM has a modular structure with each module being developed in as much detail as the existing level of knowledge permits. This structure will enable continuous improvements to be made in the light of new research. The model deals with:

- The interception of rainfall by the plant cover;

- The volume and kinetic energy of the rainfall reaching the ground surface as direct through fall and leaf drainage;

- The volume of stremflow;

- The volume of surface depression storage;

- The detachment of soil particles by raindrop impact and by runoff;

- Sediment deposition; and

- The transport capacity of the runoff.

20.6 The WEPP (Water Erosion Prediction Project)

WEPP is a process-based continuous simulation erosion model developed by the USDA-ARS that is applicable to both hill-slopes and watersheds, as illustrated in Fig. 20.3. An advantage of WEPP over other existing models such as the popular Universal Soil Loss Equation is that soil loss is estimated spatially at a minimum of 100 points along a profile and deposition of sediment also can be predicted. In other words, soil loss and deposition on a complete continuous hill-slope profile can be calculated, which is important in watershed modeling because it enables enhanced predictions of sediment yields to channels and to the watershed outlet. Additionally, runoff and soil loss are predicted for every rainfall event, allowing detailed temporal analyses and development of probability distributions.

The WEPP watershed model is an extension of the WEPP hillslope model that can be used to estimate watershed runoff and sediment yield. The application of WEPP to a watershed requires that hill slopes be delineated and channels identified. Each hillslope (represented as a rectangle in WEPP) must have a representative length (L), width (W), and slope profile. Hillslopes drain into the top, left side, or right side of a channel, eventually leading to the watershed outlet.
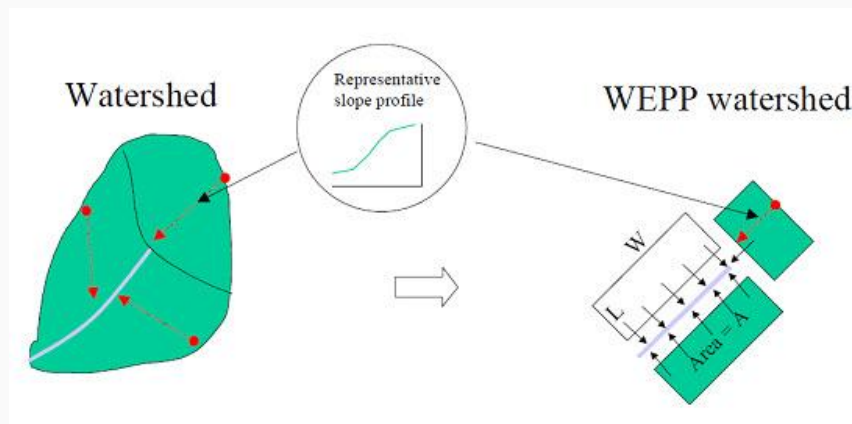
Fig. 20.3. Watershed discretization for WEPP.
(Source: http://www.agteca.com/TomThesis/chapter1.pdf)

The erosion model within WEPP applies the continuity equation for sediment transport downslope in the form (Foster & Meyer, 1972):

$dQ_s/ dx = D_i + D_f$

Where,

Q_s is the sediment load per unit width per unit time, x is the distance downslope, D_i is the delivery rate of particles detached by Interrill erosion to rill flow and D_f is the rate of detachment or deposition by rill flow. The inter-rill erosion rate (D_i) is given by:

$D_i = K_i I^2 C_e G_e (R_s /w)$

Where,

K_i is an expression of inter-rill erodibility of the soil, I is the effective rainfall intensity, C_e expresses the effect of the plant canopy, G_e expresses the effect of ground cover, R_s is the spacing of rills and w is the width of the rill computed as a function of the flow discharge. The canopy effect is estimated by:

$$C_e = 1 - Fe^{-0.34PH}$$

Where,

F is the fraction of the soil protected by the canopy and PH is the canopy height. The ground cover effect is estimated by:

$$G_e = e^{-2.5gi}$$

Where,

gi is the fraction of the Inter-rill surface covered by ground vegetation or crop residue.

The rate of detachment of soil particles by rill flow (D_f) is given by:

$$D_f = D_c (1 - Q_s / T_c)$$

Where,

D_c is the detachment capacity, Q_s is the sediment load in the flow and T_c is the sediment load at transport capacity. Detachment capacity is expressed as:

$$D_c = K_r (\tau - \tau_c)$$

Where,

K_r is the rill erodibility of the soil, t is the flow shear stress acting on the soil and τ_c is the critical flow shear stress for detachment to occur. The transport capacity of the flow is obtained from:

$$T_c = k_t \tau^{3/2}$$

Where,

k_t is a transport coefficient and τ is the hydraulic shear acting on the soil. Net deposition occurs if the sediment load is greater than the transport capacity.

20.7 CREAMS Model

CREAM is a field scale model for predicting runoff, erosion, and chemical transport from agricultural management systems. A schematic diagram of the model is shown in Fig. 20.4. It is applicable to field-sized areas. It consists of three major components: hydrology, erosion/sedimentation, and chemistry. CREAMS can operate on individual storms but can also predict long term averages (2-50 years). The objectives of the model were:

Gulley and Ravine Control Structures

- The model must be physically based and not require calibration for each specific application,

- The model must be simple, easily understood with as few parameters as possible and still represent the physical system relatively accurately,

- The model must estimate runoff, percolation, erosion, and dissolved and adsorbed plant nutrients and pesticides and,

- The model must distinguish between management practices.

Based on these objectives, since the management practices were usually on a field basis, the size of a field to represent the scale of the model was needed. A field is defined in the context of the CREAMS model as a management unit having

1) A single land use,

2) Relatively homogeneous soils,

3) Spatially uniform rainfall, and

4) Single management practices, such as conservation tillage or terraces.

Processes and Approach

The hydrologic component consists of two options. When only daily rainfall data are available to the user, the SCS curve number model is used to estimate surface runoff. If hourly or breakpoint rainfall data are available, an infiltration-based model is used to simulate runoff. Water movement through the soil profile is modeled using a simple capacity approach, with flow occurring when a layer exceeds field capacity. The erosion component maintains elements of the USLE, but includes sediment transport capacity for overland flow. The plant nutrient sub-model of CREAMS has a nitrogen component that considers mineralization, nitrification, and denitrification processes. Plant uptake is estimated, and nitrate leached by percolation out of the root zone is calculated. Furthermore, both the nitrogen and phosphorus parts of the nutrient component use enrichment ratios to estimate that portion of the two nutrients transported with sediment. The pesticide component considers foliar interception, degradation, and wash off, as well as adsorption, desorption, and degradation in the soil. Several of the equations developed for the CREAMS model have been used or modified within other models, such as WEPP, SWAT.

Sediment movement down slope obeys continuity of mass:

$dq_s/dx = D_L + D_F$

Where,

q_s is the sediment load per unit width per unit time, x is the distance downslope (m),

D_L is the lateral inflow of sediment (Interrill erosion) (mass per unit area per unit time, i.e. kg m^{-2} s^{-1}), and

Gulley and Ravine Control Structures

D_F is the detachment or deposition of sediment by flow (mass per unit area per unit time, i.e. $kg\ m^{-2}\ s^{-1}$)

The time terms of the full continuity equation drop out under the assumption of quasi-steady state conditions.
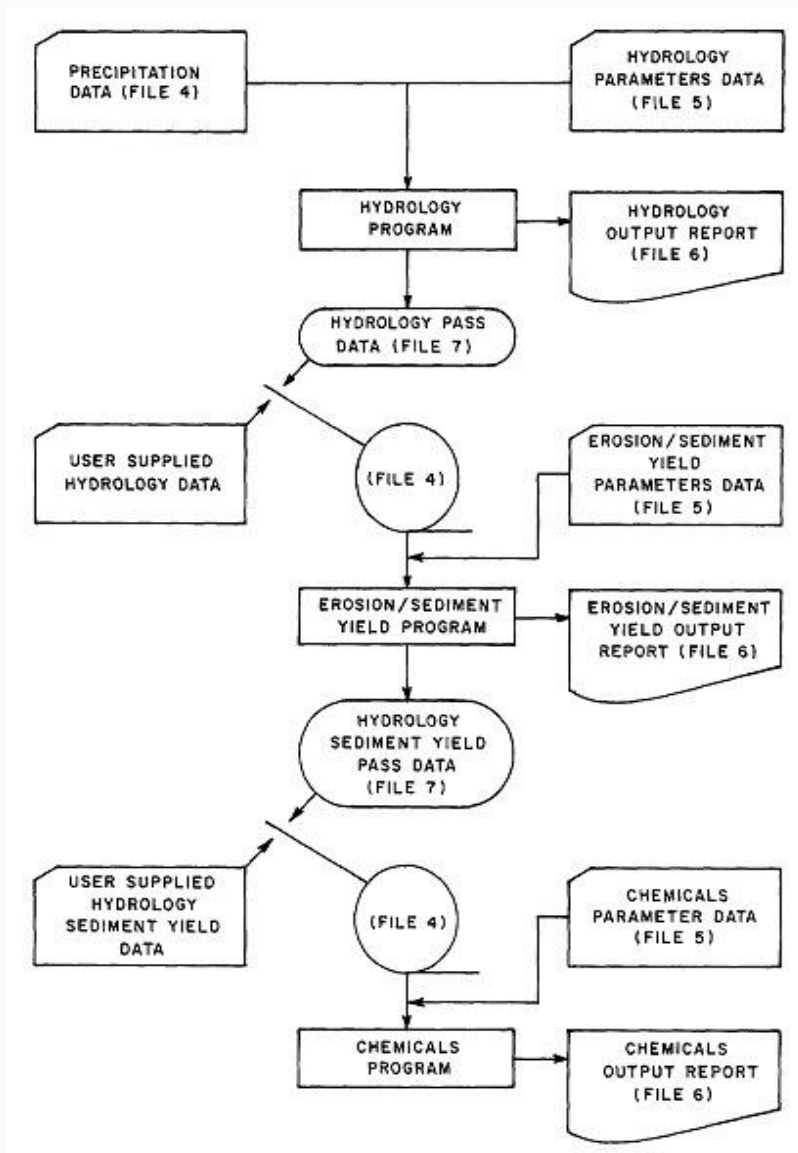
Fig. 20.4. Schematic representation of flow of CREAMS programs. (Source: http://www.tifton.uga.edu/sewrl/Gleams/creams3.pdf)

Lesson 21 Models for Predicting Sediment Yield - II

21.1 Agricultural Non-Point Source (AGNPS) Model

Agricultural Non-Point Source Pollution Model (AGNPS) is a joint USDA - Agricultural Research Service (ARS) and -Natural Resources Conservation Service (NRCS) system of computer models developed to predict non-point source pollutant loadings within agricultural watersheds. It contains a continuous simulation surface runoff model designed to assist with determining Best Management Practices, and for risk & Benefit/ Cost analyses.

The set of computer programs consist of:

(1) Input generation & editing as well as associated databases;

(2) The "annualized" science & technology pollutant loading model for agricultural-related watersheds (Ann AGNPS);

(3) Output reformatting & analysis; and

(4) The integration of more comprehensive routines (CCHE1D) for the stream network processes;

(5) A stream corridor model (CONCEPTS);

(6) An in-stream water temperature model; and

(7) **Several Related Simulation Models:** Not all of the models are electronically linked but there are paths of common input/output that, with the use of standard text editors, can be linked.

Summaries of the capabilities of the components of AGNPS are provided through the menu links on the index page. More detailed descriptions of the components, with example datasets, and the programs can be found at the AGNPS download page. Many have also registered as Cooperate users who are using the model or working with AGNPS and are provided support by the AGNPS team. Users are invited to register at the download page where individuals can see others that are using the model that might be a basis for further cooperation.

21.2 The LISEM Model

The Limburg Soil Erosion Model (LISEM) is a physically-based hydrological and soil erosion model, which can be used for planning and conservation purposes. LISEM simulates runoff and sediment transport in catchments caused by individual rainfall events. Processes incorporated in the model are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, detachment by overland flow, and transport capacity of the flow.

Gulley and Ravine Control Structures

Also, the influence of tractor wheels, small paved roads (smaller than the pixel size) and surface sealing on the hydrological and soil erosion processes is taken into account. For infiltration and vertical transport of water in the soil, a LISEM user has the following options: (0) no infiltration; (1) Richards' equation for uniform soils; (2) Richards' equation for soils and wheel tracks; (3) Richards' equation for soils, wheel tracks and crusts; (4) Holtan; (5) one-layer Green-Ampt and (6) two-layer Green-Ampt. The Richards' equation is solved separately for uncrusted soils, crusted soils and wheel tracks. In areas without detailed knowledge of soil physics, the empirical Holtan/Overton infiltration equation (e.g. Beasley et al., 1980; De Roo, 1993b) can be used. However, the Holtan equation only simulates Hortonian overland flow; saturation overland flow is not simulated. Using the Richards-based sub-model, one can simulate overland flow. In other cases, the user may choose a one or two layer Green & Ampt model.

The major differences between LISEM and other erosion models are:

On a GIS level LISEM uses a raster type representation of the catchment, such as in ANSWERS, which allows for a detailed representation of the processes. This is different from other process-based models such as EUROSEM or WEPP that use large polygon type elements;

On a programming level LISEM is constructed with a specially designed spatial modeling language which allows for great flexibility (Fig. 21.1);

On a process level LISEM comes conceptually close to EUROSEM and WEPP, while e.g. ANSWERS uses many empirical relationships. The possible use within LISEM of the SWATRE solution of the Richards' equation makes it more physically-based. The user also can choose Green and Ampt or the Holtan equation.
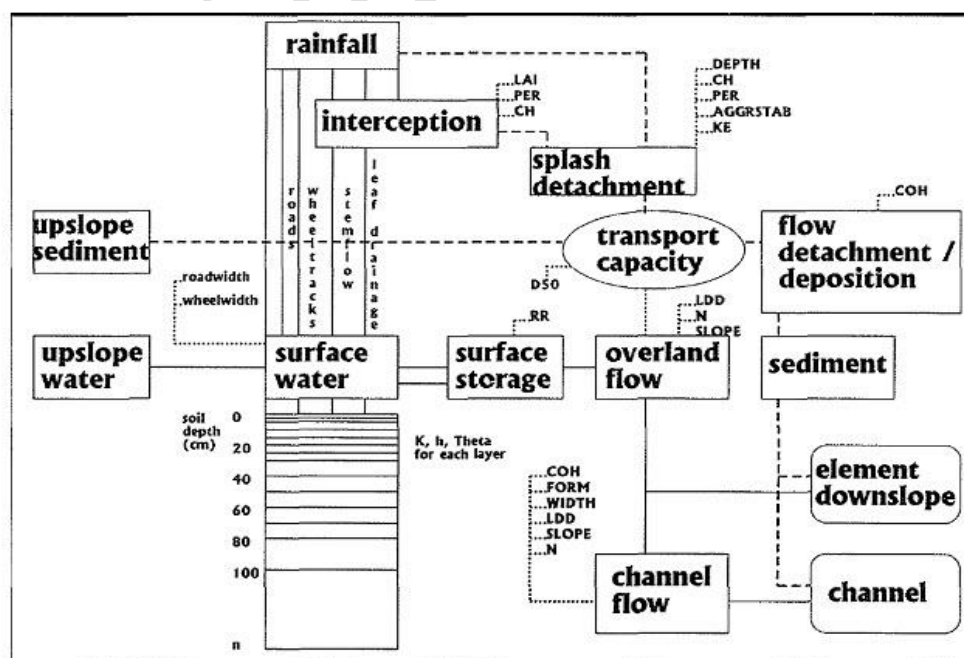
Fig. 21.1. Processes involved in the LISEM Model.
(Source: http://www.iahs.info/redbooks/a235/iahs_235_0395.pdf)

21.3 Erosion-Productivity Impact Calculator (EPIC)

The Erosion-Productivity Impact Calculator (EPIC) (Williams et al. 1984) model was originally developed to assess the effect of soil erosion on soil productivity. It was used for that purpose as part of the 1985 RCA (1977 Soil and Water Resources Conservation Act of USA) analysis. Since the RCA application, the model has been expanded and refined to allow simulation of many processes important in agricultural management.

EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally field-sized, up to 100 ha (247 ac) (weather, soils, and management systems are assumed to be homogeneous). The major components in EPIC are: weather simulation, hydrology, erosion sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control.

The EPIC component for water-induced erosion simulates erosion caused by rainfall and runoff and by irrigation (sprinkler and furrow). To simulate rainfall/ runoff erosion, EPIC contains six equations- the USLE (Wischmeier and Smith, 1978), the Onstad-Foster modification of the USLE (Onstad and Foster, 1975), the MUSLE (Williams, 1975), two recently developed variations of MUSLE, and a MUSLE structure that accepts input coefficients. Only one of the equations (user specified) interacts with other EPIC components. The **six** equations are identical except for their energy components. The USLE depends strictly upon rainfall as an indicator of erosive energy. The MUSLE and its variations use only runoff variables to simulate erosion and sediment yield. The Onstad-Foster equation contains a combination of the USLE and MUSLE energy factors. The original EPIC wind erosion model (WEQ) required daily mean wind speed as a driving variable. The new EPIC wind erosion model, Wind Erosion Continuous Simulation (WECS), requires the daily distribution of wind speed to take advantage of the more mechanistic erosion equation. The new approach estimates potential wind erosion for a smooth bare soil by integrating the erosion equation through a day using the wind speed distribution. Potential erosion is adjusted using four factors based on soil properties, surface roughness, cover, and distance across the field in the wind direction. The EPIC model with $C0_2$ capabilities has been used in several major studies in the United States.

21.4 Silt Yield Index Model

The Silt Yield Index (SYI) is defined as the Yield per unit area and SYI value for hydrologic unit is obtained by taking the weighted arithmetic mean over the entire area of the hydrologic unit by using suitable empirical equation. The Silt Yield Index Model developed by All India Soil & Land Use Survey (Dept of Agriculture, Govt. of India) was used for calculating sediment yield Index.

Estimation of Soil Loss Using Silt Yield Index (SYI) Method

The Silt Yield Index Model (SYI), considering sedimentation as product of erosivity, erodibility and areal extent was conceptualized in the All India Soil and Land Use Survey (AISLUS) as early as 1969 and has been in operational use since then to meet the requirements of prioritization of smaller hydrologic units. The erosivity determinants are the

climatic factors and soil and land attributes that have direct or reciprocal bearing on the unit of the detached soil material.

The relationship can be expressed as:

Soil erosivity = f (Climate, physiography, slope, soil parameters, land use/land cover, soil management)

The erosivity is simulated with the sediment yield weightage value which is based on assessment of the composite effect of assemblage of erosivity determinants. Whereas, the delivery ratio is adjudged by the likely delivery of the eroded material into the reservoir.

Prioritization of Watersheds/Sub-watersheds:

The prioritizations of smaller hydrologic units within the vast catchments are based on the Silt Yield Indices (SYI) of the smaller units. The boundary values or range of SYI values for different priority categories are arrived at by studying the frequency distribution of SYI values and locating the suitable breaking points. The watersheds/sub-watersheds is subsequently rated into various categories corresponding to their respective SYI values.

The application of SYI model for prioritization of sub-watersheds in the catchment areas involves the evaluation of:

a) Climatic factors comprising total precipitation, its frequency and intensity,

b) Geomorphic factors comprising land forms, physiography, slope and drainage characteristics,

c) Surface cover factors governing the flow hydraulics and

d) Management factors.

The data on climatic factors can be obtained for different locations in the catchment area from the meteorological stations whereas field investigations are required for estimating the other attributes.

The various steps involved in the application of model are:

- Preparation of a framework of sub-watersheds through systematic delineation

- Rapid reconnaissance surveys on 1:50,000 scale leading to the generation of a map indicating erosion-intensity mapping units.

- Assignment of weightage values to various mapping units based on relative silt-yield potential.

- Computing Silt Yield Index for individual watersheds/sub watersheds.

- Grading of watersheds/sub-watersheds into very high, high medium, low and very low priority categories.

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The area of each of the mapping units is computed and silt yield indices of individual sub watersheds are calculated using the following equations:

a. Silt Yield Index

SYI = (Σ (A_i x W_i) x 100)/ A_w;

Where,

 i = 1 to n

Where,

A_i = Area of ith unit (EIMU)

W_i = Weightage value of ith mapping unit

n = No. of mapping units

A_w = Total area of sub-watershed.

The SYI values for classification of various categories of erosion intensity rates are given in Table-21.1

Table 21.1. Land use pattern of a sample catchment area

Category	Area (ha)	Percentage
Dense Vegetation	8650	51.92
Open Vegetation	3472	20.83
Scrub	2888	16.13
Agriculture land	198	1.19
Rocky outcrops	1591	9.55
Water body	52	0.31
Settlement	12	0.07
Total	**16661**	**100.00**

Table 21.2. Criteria for erosion intensity rate priority categories

Priority categories	SYI Values
Very high	> 1300
High	1200-1299
Medium	1100-1199
Low	1000-1099
Very Low	<1000

(Source:http://apspcb.org.in/pdf/28_12_10/NJC%20HEP%20REPORT-8.12.10/EMP%20Report%20Nyamjangchhu%20HEP_6.12.10/Chapter-2%20CAT%20Plan.pdf)

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Any water resource project developer in India, such as irrigation project, hydro-electric project, etc. (private or government) is mandated by the Ministry of Environment and Forests to consider the very highly and highly eroded sub-watersheds (See Table 21.2) to bring under the purview of Catchment Area Treatment (CAT) Plan. A CAT plan usually comprises engineering and other measures for erosion control. The budget for CAT work in included in the project budget. The CAT is executed by the Forest Department of the state.

21.5 The ANSWER Model

Area Non-point source watershed environment response simulation (ANSWER) (Beasley and Huggins, 1982) uses a distributed parameter approach and is limited to a single storm event. Hydrology model components include rainfall interception, infiltration, surface detention and surface retention. A sediment continuity equation is employed which describes the process of soil detachment, transport and deposition. A watershed (up to 10,000 ha) being modeled is divided into a series of small independent element (1 to 4 ha). The use of small element allows considerable spatial details in representing topography, soils and land use but the building of input files and interpreting output requires significant time and considerable knowledge of the model and its operation.

21.6 SWAT Model

The Soil and Water Assessment Tool (SWAT) model was developed by US Department of Agriculture – Agriculture Research Service (USDA-ARS). It is a conceptual model that functions on a continuous time step. Model components include weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, channel routing, and pond/reservoir routing. Agricultural components in the model include fertilizer, crops, tillage options, and grazing and have the capability to include point source loads (Neitsch et al., 2001a; Neitsch et al., 2001b). The SWAT model predicts the influence of land management practices on constituent yields from a watershed. SWAT is the continuation of over 30 years of model development within the US Department of Agriculture's Agricultural Research Service. SWAT is a public domain model which is actively supported by the USDA Agricultural Research Service at the Grassland, Soil, and Water Research Laboratory in Temple, Texas, USA.

The SWAT model simulates hydrology as a two-component system, comprised of land hydrology and channel hydrology. The land portion of the hydrologic cycle is based on a water mass balance. Soil water balance is the primary considerations by the model in each HRU, which is represented as (Arnold et al., 1998):

$$SW_t = SW + \sum (R_i - Q_i - ET_i - P_i - QR_i)$$

Where,

SW is the soil water content, i is time in days for the simulation period t, and R, Q, ET, P and QR respectively are the daily precipitation, runoff, evapotranspiration, percolation, and return flow. Water enters the SWAT model's watershed system boundary predominantly in the form of precipitation. Precipitation inputs for hydrologic calculations can either be measured data or simulated with the weather generator available in the SWAT model. Precipitation is partitioned into different water pathways depending on system

characteristics. The water balance of each HRU in the watershed contains four storage volumes: snow, the soil profile (0-2 m), the shallow aquifer (2-20 m) and the deep aquifer (>20 m). The soil profile can contain several layers. The soil water processes include infiltration, percolation, evaporation, plant uptake, and lateral flow. Surface runoff is estimated using the SCS curve number or the Green-Ampt infiltration equation. Percolation is modeled with a layered storage routing technique combined with a crack flow model. Potential evaporation can be calculated using Hargreaves, Priestly-Taylor or Penman-Monteith method (Arnold et al., 1998).
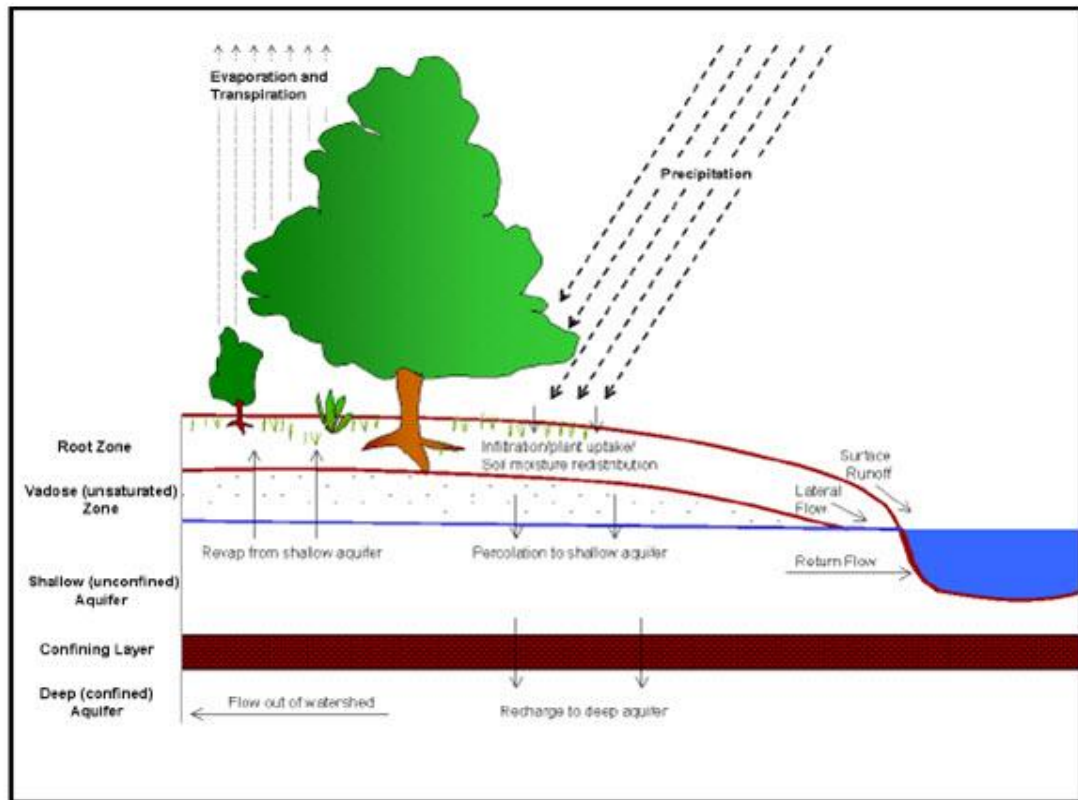
Fig. 21.1. Hydrologic cycle considered by SWAT model. (Source: http://arkansaswater.org/materials/C%20SWAT%20Model%20Description%2004-20-2006.pdf)

21.7 MIKE SHE

MIKE SHE is a comprehensive, deterministic, distributed and physically based modeling system for the simulation of all major hydrological processes occurring in the land phase of the hydrological cycle. It simulates water flow, water quality and sediment transport. MIKE SHE comprises a number of comprehensive pre and post processors including digitizing, graphical editing, contouring, grid averaging and graphical result presentation with option for display of animation. Application of the model on PCs is limited because of the large number of computation that must be made.

MIKE SHE is applicable to a wide range of water resources and environmental problems related to surface water and groundwater system and the dynamic interaction between these. It is applicable on spatial scales from a single soil profile (infiltration studies) to large regions, which may include several river catchments.

21.8 HSPF Model

The hydrological simulation program-Fortran (HSPF) (Johansen et. al., 1984) is a mathematical model developed under EPA sponsorship to simulate hydrologic and water quality processes in natural and manmade water system. HSPF is a continuous simulation model and requires continuous data (generally hourly rainfall) to derive the simulations. This model requires input parameters for each of the various processes. Without calibration data, it can be difficult to verify the flows computed by this model.

Over the years, development activities and model enhancement, along with the model application, have continued to improve the model's capabilities and preserve its status as a state-of-art-tool for watershed analysis.

Module 4: Vegetative and Structural Measures for Erosion and Gully Control

Lesson 22 Soil Erosion Control Measures

22.1 Introduction

Soil erosion takes place both due to natural causes and anthropogenic factors. The adverse effects of uncontrolled soil erosion are loss of valuable top soil lowering crop productivity per unit of land, sedimentation in rivers and irrigation canals drawing water from the rivers reducing their carrying capacity, sedimentation of reservoirs reducing their active life, structural damages to the buildings and formation of gullies and ravines, to name a few important ones. Soil erosion control measures are adopted to reduce or minimize the intensity of the aforesaid adverse effects. Catchment Area Treatment (CAT) is adopted to reduce soil loss from catchments due to runoff flow, after ascertaining erosion severity on sub-watershed basis. CAT comprises mechanical (engineering) and vegetative (afforestation) measures. Mechanical and vegetative practices on agricultural lands are employed on the milder slopes for conservation of soil, by farming across the slope of the land. The basic principle underlying this approach is to cause reduction in the effect of the runoff velocity and, thereby reduce soil erosion. On steeper slopes, mechanical measures (such as terracing) and other structures are constructed to reduce the effect of the slope on runoff velocity. The following types of vegetative and mechanical practices are being used at present:

22.1.1 Vegetative Practices

(i) Contouring

(ii) Strip cropping

(iii) Tillage operations

(iv) Mulching

22.1.2 Mechanical Practices

(i) Terracing

(ii) Bunding

(iii) Grassed waterways and diversions

Vegetative practices are described in this lesson and mechanical practices are described in the subsequent lessons.

22.2 Contouring

Contouring is the practice of cultivation along contours, as illustrated in Fig. 22.1, laid across the prevailing slopes of the land where all farming operations, such as ploughing, sowing, planting, cultivation, etc. are carried out approximately on contours.

Fig. 22.1. Contouring. (Source: http: //www. watershedbmps.com)

The intercultural operations create contour furrows, which along with plant stems act as barriers to the water flowing down the slope. In between two adjacent ridges runoff or irrigation water is detained for a longer period of time, which in turn, increases the opportunity time for the water to infiltrate into the soil and increase the soil moisture. To lay a contour farming system, contour guide lines are laid out first and tillage operations are carried out simultaneously. Experimentally it has been observed (Antal, 1986) that reduction in the intensity of soil erosion, owing to water, by contour ploughing is about 30% of that by ploughing along the slope, and there is increase in moisture content by about 40% and reduction in surface runoff by about 13%. Furrow cultivation on contours has been found to be the most effective soil conservation measure. Contour farming is recommended for lands with the slope range of 2 to 7%.

22.3 Strip Cropping

Strip cropping is the practice of growing strips of crops having poor potential for erosion control, such as root crops (which are intertilled crops), cereals, etc., alternated with strips of crops having good potential for erosion control, such as fodder crops, grasses, etc. which are close growing crops. Strip cropping is a more intensive farming practice than farming only on contours. Close growing crops act as barriers to runoff flow and reduce the runoff velocity generated from the strips of intertilled crops, and eventually reduce soil erosion.

22.3.1 Purpose of Strip Cropping is to:

(a) Reduce soil erosion from water and transport of sediment and other water-borne contaminants

(b) Reduce soil erosion from wind

(c) Protect growing crops from damage by wind-borne soil particles.

22.3.2 Methods of Strip Cropping:

(a) Contour strip cropping

(b) Field strip cropping

(c) Buffer strip cropping

(a) Contour Strip Cropping

In contour strip cropping, alternate strips of crops are sown more or less along the contours, similar to contouring. Suitable rotation of crops and tillage operations are followed during the farming operations. Fig. 22.2 shows contour strip cropping.

Fig. 22.2. Contour strip cropping. (Source: https: //www.weru.ksu.edu)

(b) Field Strip Cropping

In a field layout of strip cropping, as shown in Fig. 22.3, strips of uniform width are laid out across the prevailing slope, while protecting the soil from erosion by water.

Fig. 22.3. Field strip cropping. (Source: https: //www.weru.ksu.edu)

To protect the soil from erosion by wind, strips are laid out across the prevailing direction of wind. Such practices are generally followed in areas where the topography is irregular, and the contour lines are too curvy for laying the farming plots.

(c) Buffer Strip Cropping

Buffer strip cropping is practiced where uniform strips of crops are required to be laid out for smooth operation of farm machinery, while farming on a contour strip cropping layout. Buffer strips of legumes, grasses and similar other crops are laid out between the contour strips as correction strips, as illustrated in Fig. 22.4. Buffer strips provide very good protection and effective control of soil erosion from strips of intertilled crops.

Fig. 22.4. Buffer strip cropping. (Source: https://www. passel.unl.edu)

22.4 Tillage Operations

Tillage operations carried out for conservation of soil are

(a) Minimum tillage

(b) No tillage

(c) Strip tillage

The special benefit of tillage operations are to:

(1) Increase the soil infiltration capacity

(2) Improve the soil moisture retention capacity

(3) Improve the humus content of soil

(4) Create a rough land surface to protect it against erosion by water or wind.

Minimum Tillage

It is the operation in which tillage and sowing are combined in one operation, as illustrated in Fig. 22.5. Such operations create a coarse soil surface and fine lumps of soil between rows. The loose and porous texture of the soil allows a good infiltration capacity. The surface runoff by this operation is reduced by about 35% and soil erosion by about 40%.

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Fig. 22.5. Minimum tillage. (Source: https: //www. dave-koenig.com)

No Tillage

In the no-tillage system of operation, the soil surface is not disturbed much and left more or less intact. The operations performed are under cutting, loosening and drying of the upper soil layer, so that weeds do not grow and stubbles of the previous crop remain as such in the field. When there are no weeds, the under cutting operations are not required, and seeds are sown directly into the soil by special types of seed drills. Incidentally, the shifting (Jhoom) cultivation, as illustrated in Fig. 22.7, prevalent in north-east India, is perhaps the best example of no-tillage traditionally followed since hundreds of years. In jhoom cultivation, a part of a forest land is burnt to clear it and seeds are manually dibbled without any ploghing or major soil disturbance. When the naturally occurring soil nutrients are exhausted, the land is abandoned and a new piece of forest land is selected for burning and subsequent cultivation. However, this method of cultivation has a risk of aggravating soil erosion problem if practiced on hill slopes (which usually is the case).

Fig. 22.6. Terrace rice cultivation in Phek district (Jhoom Cultivation).(Source: http://gbpihedenvis.nic.in/html/vol16_2/S.S.%20Rathore.htm)

It is found that reduction in soil erosion up to 70% has been obtained through this method of tillage.

Strip Tillage

This operation is an improvement over the no tillage system. In this type of cultivation, narrow strips of approximately 0.2 m width and 0.1 m depth are generally laid out following the contour, and the land between the strips left uncultivated. These are also called loosening strips. In the constructed narrow strips, there are no stubbles, which help in sowing operations and facilitate better plant growth. Fig. 22.7 and 22.8 shows strip tillage done by tractor drawn implement and animal drawn implement.

Fig. 22.7. Strip-tillage. (Source: https: //www. bighambrothers.com)
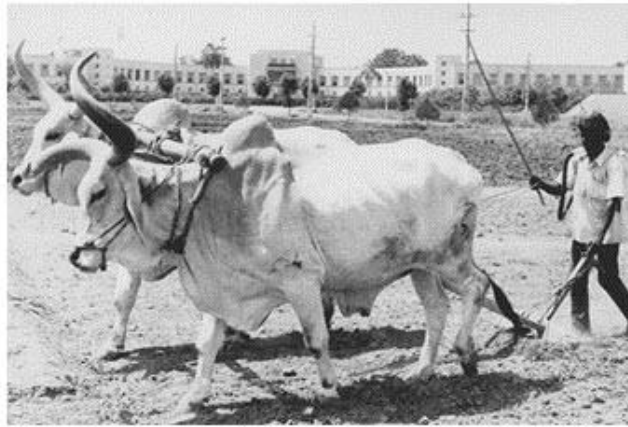
Fig. 22.8. Bullock-drawn shallow chisel desi plough.
(Source: http://www.ilo.org/oshenc/images/stories/enlarged/Part10/AGR_imgs/AGR100F1.j
pg)

The farm implement normally used for conservation tillage operations are:

(1) V-shaped sweeps

(2) Arrow shaped blades for control of erosion caused by water

(3) Chisel like blades for control of erosion caused by wind

(4) Rod weeders etc.

22.5 Mulching

Mulches (soil covers) are used to minimize rain splash, reduce evaporation, control weeds, reduce temperature of soil in hot climates, and allow temperature which is conducive to microbial activity. A view of munches is shown in Fig. 22.9. Stubbles, trash, other type of vegetation and polythene are some of the most common types of mulches used. These materials are spread over the land surface. Mulches help in reducing the impact energy of

rain water, prevent splash and destruction of soil structure, obstruct the flow of runoffs to reduce their velocity and prevent inter-rills erosion, and help in improving the infiltration capacity by maintaining a conductive soil structure at the top surface of the land.

Fig. 22.9. Mulching. (Source: https: //www. thailand.ipm-info.org)

Lesson 23 Terracing

23.1 Introduction

A terrace is an earth embankment, constructed across the slope, to control runoff and minimize soil erosion. A terrace acts as an intercept to land slope, and divides the sloping land surface into horizontal or mildly sloping strips of small width. It has been found that soil loss is proportional to the square root of length of slope, i.e. by shortening the length of run, soil erosion is reduced. Terrace agriculture is a common technique used to cultivate the land in the steeply sloping terrain of the hills in India and other parts of Asia. It is also easier to plough, sow and harvest on a leveled surface than on a steep slope. Terrace cultivation of Ranikhet at Uttrakhand state of India is shown in fig. 23.1.

Fig. 23.1. Terrace cultivation. (Source: http:// www.trekearth.com)

23.2 Types of Terrace
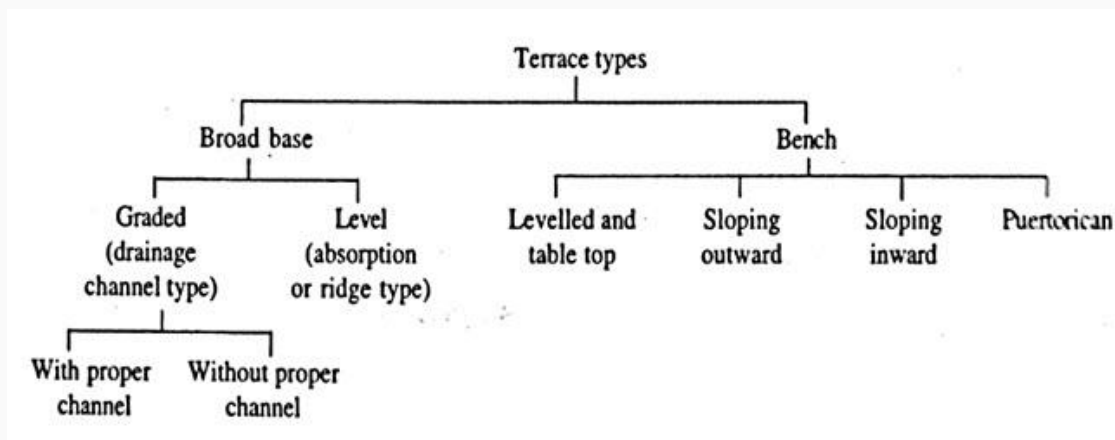
Fig. 23.2. Type of terraces. (Source: Das, 2002)

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Terraces are classified (Fig. 23.2) into two major types:

(A) Broad-base terrace

(B) Bench terrace

(A) Broad-Base Terrace

Broad base terraces were developed by farmers of western countries (USA). The cross sectional view of a broad-base terrace is given in Fig. 23.3.
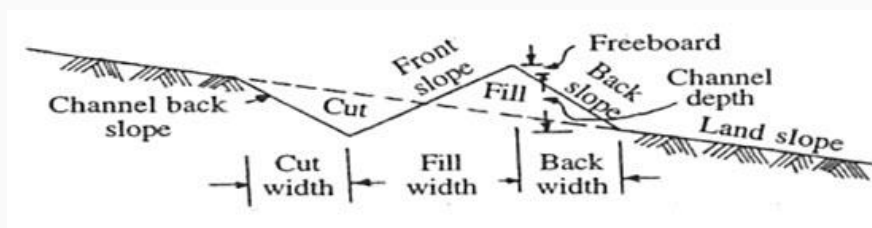
(a)Triangular design
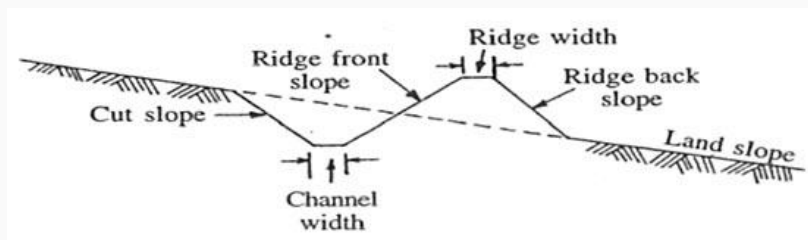
(b)Broad-base terrace with channel slope (trapezoidal design)

Fig. 23.3. Cross sectional view of a broad-base terrace. (Source: Das, 2002)

These types of terraces consist of a ridge which has a fairly broad base and a flatter slope, so that farm machinery can easily pass over the ridge. On these types of terraces, even ridge area is cultivated and no land is lost to agricultural operations because of terracing.

Broad-base terraces are of two types:

(i) Graded terraces

(ii) Level terraces

(i) Graded Terraces

Graded or drainage terraces are constructed in high rainfall areas (> 600mm), where the excess runoff needs to be removed quickly and safely to protect the crop from water-logging.

Graded broad-base terrace are also of two types:

(a) Graded terrace without proper channel

(b) Graded terrace with proper channel

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(a) Graded Terrace without Proper Channel

The whole strip of the terrace is used as a channel for conveyance of the runoff to the outlet in this case. It is adopted where excess runoff generated is low and water can be allowed more time to get absorbed in the soil increasing the soil moisture.

(b) Graded Terrace with Proper Channel

The purpose of this type of terrace is to remove excess runoff water with low velocity so as to minimize soil erosion. Runoff velocity in this type of terrace is equal to non-erosive velocity. The channels are shallow and wide, with a low gradient. Such terraces are constructed on land slope of 5 to 15%. Channel grade is provided from 0.1 to 0.6%, where 0.4% is the most common grade.

(ii) Level Terraces

Level or ridge terraces are also of two types- wide based and narrow based-depending on the width of the ridge and channel. Narrow based terraces have widths in the range of 1.2 to 2.5 m, and are not suitable for mechanized cultivation. These narrow-based terraces are popular in India and are called contour bunds.

(A) Bench Terrace

Bench terraces are constructed to reduce the slope of hill sides to reduce runoff flow velocity, and thus prevent soil erosion. In hilly areas, bench terraces are extensively used as agricultural field plots, but their construction is costly. Bench terraces are constructed on hill sides which has gradient in the range of 15 to 30% or more and the land surface has a medium to high degree of soil erosion. Different components of bench terraces are shown in Fig. 23.4.
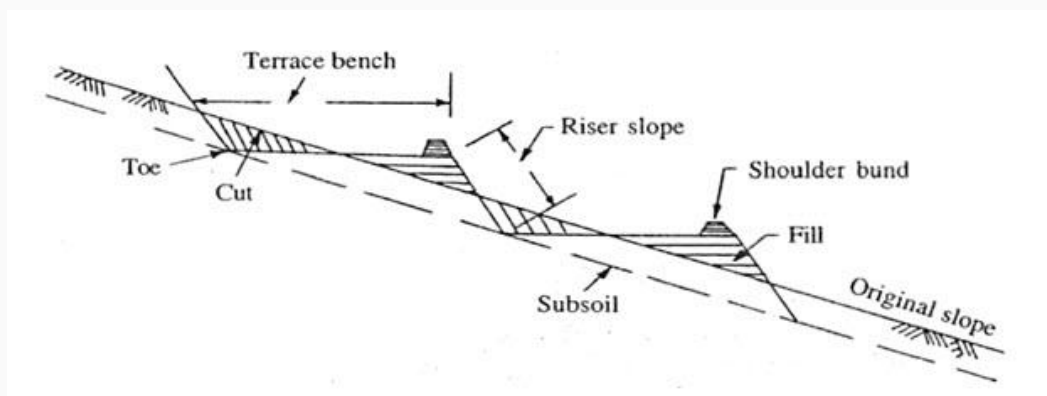
Fig. 23.4. Components of a bench terrace. (Source: Das, 2002)

During the construction of such type of terraces, it is assumed that the excavated earth from the upper half of the terrace is deposited on the lower half of the terrace. It implies that cut is equal to fill.

Depending upon the soil, the climate and the crop, bench terraces are classified into following categories:

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(i) Leveled and table top

(ii) Outward sloping

(iii) Inward sloping

(iv) Puertorican

(i) Leveled and Table Top Bench Terrace

The leveled and table top type terrace (Fig. 23.5) consist of a leveled field. Leveled terraces are generally laid out in areas where crops requiring large quantity of water are grown (such as paddy). It could be places where rainfall is high or sufficient irrigation water is available. Level bench terraces are used not only for lands with slopes more than 6%, but also for lands with slopes as mild as 1% to facilitate uniform ponding of water on the field.
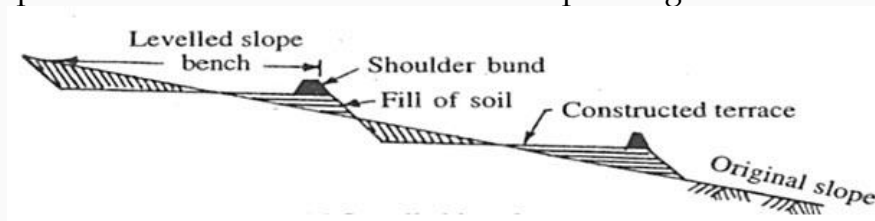
Fig. 23.5. Leveled bench terrace. (Source: Das, Ghanshyam., 2002)

(ii) Outward Sloping Bench Terrace

Outward sloping bench terraces (Fig. 23.6) are laid out in areas where the depth of soil is not sufficient for leveling work. At deeper cuts, the infertile subsoil is likely to be exposed to the surface. Outward sloping bench terrace also recommended in those areas where rainfall is not very high and soil erosion is not quite significant.
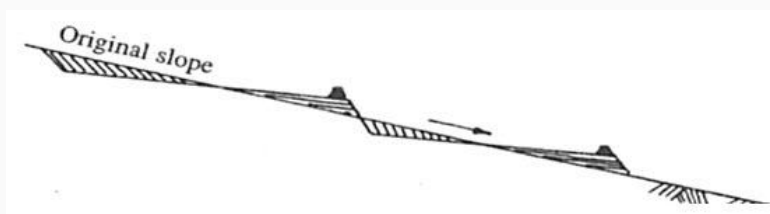
Fig. 23.6. Outward sloping bench terrace. (Source: Das, 2002)

(iii) Inward Sloping Bench Terrace

Inward sloping bench terrace (Fig. 23.7) is constructed in areas with deep permeable soils.
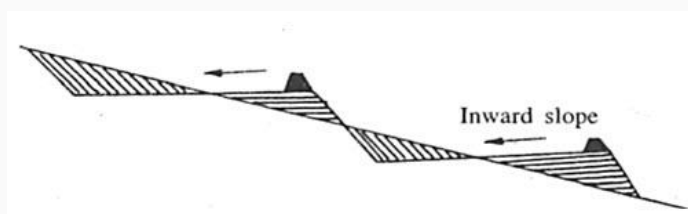
Fig. 23.7. Inward sloping bench terrace. (Source: Das, 2002)

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These are well designed terraces, and are recommended in areas with heavy rainfall. The subsequent high rate of runoff is released towards the toe end of terrace, and the runoff is safely conveyed to the outlet after allowing enough ponding time for infiltration. Such terraces are quite suitable for potato cultivation, because they provide very good drainage to furrow crops laid widthwise.

(iv) Puertorican Type Bench Terrace

It is also called California type bench terrace and is leveled in stages and shown in fig. 23.8.
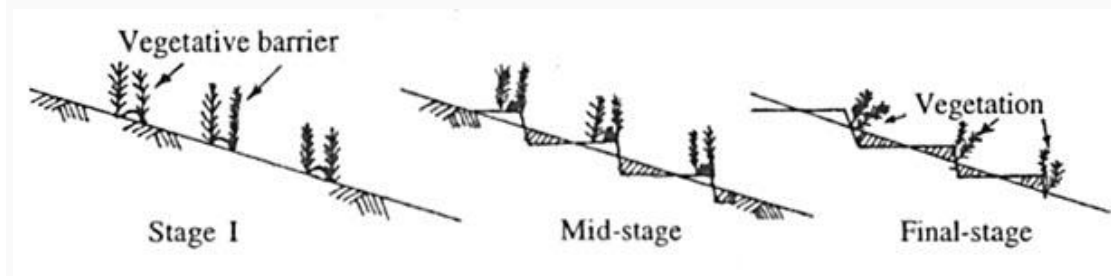
Fig. 23.8. Puertorican type bench terrace. (Stage of self-formation). (Source: Das, 2002)

23.3 Design of Terrace

23.3.1 Design of Broad-Base Terrace

The capacity of terrace channel is designed based on the expected peak flow rate. The expected peak flow rate is calculated by Rational formula, which is generally based on a recurrence interval of 10 years. The velocity of flow is calculated by Manning's formula, by taking roughness coefficient as 0.04. A suitable settlement allowance of about 20% is recommended to be provided to the new constructions.

To design terrace length, the following steps are followed:

(1) At first, the vertical interval (V.I) is determined by the empirical formula given as:

$$VI = 0.3(as + b) \qquad (23.1)$$

Where,

VI = Vertical interval, m

a = a constant dependent on geographical location (value is less than one)

s = average land slope above the terrace, %

b = a constant for soil erodibility and cover conditions during critical periods. The value of b varies within 1 to 4 for low to high intake rates.

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(2) Horizontal interval is determined by

$$\frac{s}{100} = \frac{VI}{HI} \qquad (23.2)$$

Where,

HI = horizontal interval, m

(3) Peak flow is determined by Rational formula as:

$$Q_p = 0.0028 \text{ CIA} \qquad (23.3)$$

Where,

= Peak rate of runoff (m³/s)

C = Runoff coefficient

I = intensity of rainfall equal to the duration of time of concentration (mm/h).

$$t_c = 0.0195 \ L^{0.77} \ S^{-0.85} \qquad (23.4)$$

t_c = Time of concentration (min)

L = The length of flow = terrace width (m) +length of terrace (m)

s = H/L

H = difference in elevation (m) between the most remote point and the outlet. This value is calculated by determining the drop owing to the slope gradients for terrace length + drop owing to the land slope for the horizontal width of terrace.

A = area of watershed, i.e. length × width of terrace strips (ha)

(4) Using the method of iteration, the dimensions of channel are determined by assuming different widths and depths of channel, and then comparing the computed discharge rate from the channel with the determined Q_P. These two values should be approximately same for the best designs.

(5) The values of the width and depth which gives a matching Q_P become the dimensions of the channel.

(6) A free board is added to the depth of channel to calculate height of the ridge of the terrace.

(7) From the side slopes of the ridge, the base width of the ridge is calculated by using the value of the height of the ridge as determined at step (6).

23.3.2 Design of Bench Terrace

In the design of bench terrace the following parameters are determined.

(1)Terrace spacing (vertical interval) and width

(ii)Percentage area lost due to terracing

(iii)Earth work per ha area

23.3.3 Design of Leveled and Table Top Bench Terrace
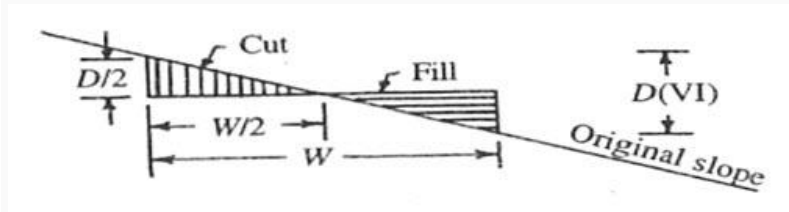
Fig. 23.9. Vertical cut table top bench terrace. (Source: Das, 2002)

For Vertical Cut (fig. 23.9):

$$\frac{s}{100} = \frac{VI}{HI} = \frac{D}{W}$$

$$D = \frac{SW}{100} \qquad (23.5)$$

$$\% \ area \ lost = \frac{actual \ length \ of \ hill \ slope - width \ of \ terrace}{actual \ length \ of \ hill \ slope} \times 100$$

$$= \frac{\sqrt{D^2 + W^2} - W}{\sqrt{D^2 + W^2}} \qquad (23.6)$$

$$Length \ of \ terrace/ha \ (L) = \frac{10^4}{HI} = \frac{10^4}{W} \qquad (23.7)$$

$$\frac{Earthwork}{ha} = cross \ sectional \ area \ of \ cut \times length \ per \ ha$$

$$= \frac{1}{2} \times \frac{w}{2} \times \frac{D}{2} \times L = \frac{DLW}{8} \qquad (23.8)$$

Where,

    D= vertical interval, m

    W= width of terrace, m

    s = original land slope, %

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For 1:1 Batter Slope:

$$\frac{s}{100} = \frac{VI}{HI} = \frac{D}{(W+D)}$$

$$D = \frac{SW}{(100-S)} \qquad (23.9)$$

$$\% \ area\ lost = \frac{actual\ length\ of\ hill\ slope - width\ of\ terrace}{actual\ length\ of\ hill\ slope} \times 100$$

$$= \frac{\sqrt{D^2+(D+W)^2}-W}{\sqrt{D^2+(D+W)^2}} \times 100 \qquad (23.10)$$

$$\frac{Length}{ha}(L) = \frac{10^4}{HI} = \frac{10^4}{(W+D)} \qquad (23.11)$$

$$\frac{Earthwork}{ha} = cross\ sectional\ area\ of\ cut \times length\ per\ ha$$

$$\frac{Earthwork}{ha} = \frac{DLW}{8} \qquad (23.12)$$

Where,

D= vertical interval, m

W= width of terrace, m

s = original land slope, %

For ½:1 Batter Slope:

$$\frac{s}{100} = \frac{VI}{HI} = \frac{D}{(W+\frac{D}{2})}$$

$$D = \frac{2SW}{(200-S)} \qquad (23.13)$$

$$\% \ area\ lost = \frac{actual\ length\ of\ hill\ slope - width\ of\ terrace}{actual\ length\ of\ hill\ slope} \times 100$$

$$= \frac{\sqrt{D^2+(W+\frac{D}{2})^2}-W}{\sqrt{D^2+(W+\frac{D}{2})^2}} \times 100 \qquad (23.14)$$

$$\frac{Length}{ha}(L) = \frac{10^4}{HI} = \frac{10^4}{(W+\frac{D}{2})} \qquad (23.15)$$

$$\frac{Earthwork}{ha} = cross\ sectional\ area\ of\ cut \times length\ per\ ha$$

$$= \frac{DLW}{8} \qquad (23.16)$$

Where,

D= vertical interval, m

W= width of terrace, m

s = original land slope, %

Lesson 24 Bunds

24.1 Introduction

Bunding is an engineering soil conservation measure used for retaining water and creating obstruction to the surface runoff for controlling soil erosion. Bunds are simple earthen embankments of varying lengths and heights, constructed across the slope. When they are constructed on the contour of the area, they are called as contour bunds and when a grade is provided to them, they are known as graded bunds. For bunding, the entire area is divided into several small parts; thereby the effective slope length of the area is reduced. The reduction of the slope length causes not only reduction of the soil erosion but also retention of the runoff water in the surrounding area of the bund. Bunds are similar to the narrow based terrace, but no agricultural practices are done on bunds except at some places, where some types of stabilization grasses are planted to protect the bund.

24.2 Types of Bunds

Bunds are of two types: (1) Contour bund and   (2) Graded bund

(1) Contour Bund

When the bunds are constructed following the same contour, they are called contour bunds. Fig 24.1 shows the layout of contour bunds in the field. Contour bunds are recommended for areas with low annual rainfall (<600 mm), agricultural field with permeable soil and having a land slope < 6%. The major requirements in such areas are prevention of soil erosion and conservation of rain water in the soil for crop use.
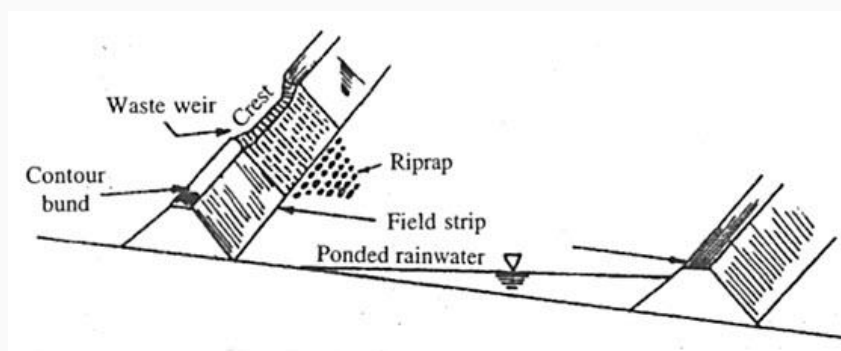
Fig. 24.1. Layout of contour bunds in field. (Source: Das, 2002)

Contour bund absorbs the runoff water stored at the upstream side of the bund. Proper height of the bund is necessary to avoid overtopping during floods. During monsoon, even in a low rainfall region, the entire runoff water cannot be stored and the excess is liable to flow over the bund. To avoid damage, waste or surplus weir (Fig. 24.2) is provided on the bunds to dispose off excess water into the next bund. This prevents water-logging.
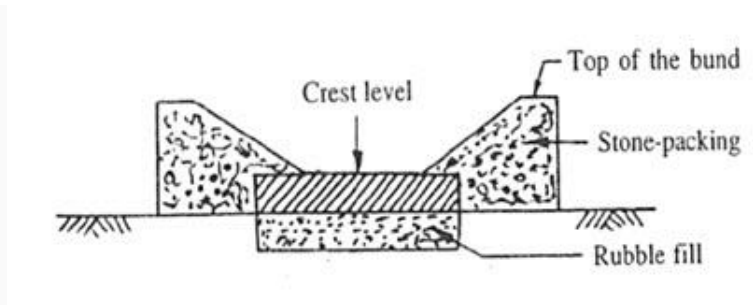
Fig. 24.2. Clear overfall stone weir. (Source: Das, 2002)

Contour bunding can be adopted on all types of permeable soil except for the clayey or deep black cotton soils as these soils have the problem of crack development causing bund failure. Clayey soil also has the problem of water-logging near the bund section, which makes the bund construction infeasible.

(2) Graded Bund

When a grade is provided along the bund for safe disposal of runoff water over the area between two consecutive bunds, they are called graded bund. Graded bunds are adopted in case of high or medium annual rainfall (>600 mm) and relatively less permeable soil areas. Graded bunds are designed to dispose excess runoff safely from agricultural field.

24.3 Design of Bunds

24.3.1 Design of Contour Bund

The design parameters required for contour bunds are

(1) Vertical interval

(2) Horizontal interval

(3) Bund cross-section

(4) Earth work due to bunding

Height of the contour bund should be enough to store the expected peak runoff for a 10 years recurrence interval. A free board of about 20% should be provided for the settlement of height.

(1) Calculation of Vertical Interval (V.I) and Horizontal Interval (H.I)

For low rainfall areas

$$VI = 0.15s + 0.6 \ (m)$$

$$and \ \frac{s}{100} = \frac{VI}{HI}$$

$$then, \ HI = \frac{VI \times 100}{s} \quad (m)$$

Gulley and Ravine Control Structures

Where,

VI = Vertical interval, m

HI = Horizontal interval, m

s = Original land slope, %

(2) Calculation of Storage Required for Runoff Volume

$$P_e = P - I \quad (m)$$

$$A = HI \times L \quad (m^2)$$

$So, runoff\ volume\ to\ be\ stored (R_V)$

$$R_V = P_e \times A \quad (m^3)$$

Where,

P = Precipitation, m

P_e = Excess rainfall depth or surface runoff, m

I = infiltration depth, m

H.I = Horizontal interval, m

L = Length of bund behind which the runoff is stored, m

A = Area of watershed behind two bunds, m².

R_V = Runoff volume to be stored, m³.

(3) Calculation of Storage Volume
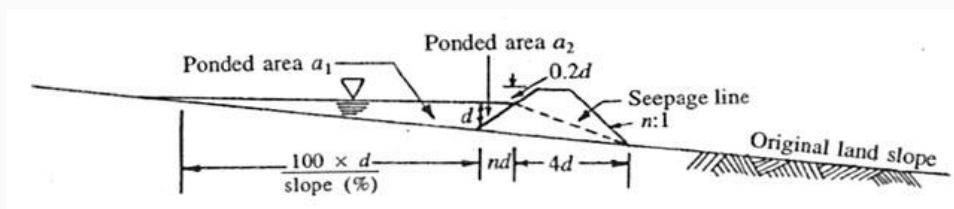
Fig. 24.3. Layout of contour bund. (Source: Das, 2002)

From the above layout of contour bund (Fig. 24.3),

$$Ponded\ area\ (a_1) = \frac{1}{2} \times \frac{100d}{s} \times d \quad (m^2)$$

$$Ponded\ area\ (a_2) = \frac{1}{2} \times nd \times d \quad (m^2)$$

$$Area\ of\ water\ stored\ behind\ the\ bund = (a_1 + a_2) \quad (m^2)$$

Gulley and Ravine Control Structures

Storage volume (S_V) = area of water stored behind the bund × length of bund (m³)

where,

d = depth of water stored behind the bund (m)

n : 1(H:V) = side slope of the contour bund

4:1 (H:V) = Seepage line slope of the bund

(4) Calculation of Depth of Water Stored Behind Bund

For total runoff absorbed by the bund,

Runoff volume (R_V) = Storage volume (S_v)

Using this relationship, the depth of water stored behind bund is calculated.

(5) Calculation of Bund Cross Section

$$Total\ height\ of\ the\ bund\ (H) = (d + 20\%\ of\ d\ as\ freeboard)\quad (m)$$

$$Base\ width(B) = (nd + 4d)\quad (m)$$

$$Top\ width(T) = (B - 2nH)\quad (m)$$

(6) Calculation of Earth Work due to Bunding

$$Lengh\ of\ contour\ bund\ per\ ha\ (L) = \frac{10^4}{HI}\quad for\ main\ bund$$

$$= \frac{10^4}{HI} \times 1.3\ for\ main\ bund\ with\ side\ and\ lateral\ bund$$

$$Earthwork\ per\ ha = cross\ sectional\ area\ of\ bund \times length\ per\ ha$$

$$= \left[\frac{1}{2} \times (B + T) \times H\right] \times L \qquad (\frac{m^3}{ha})$$

24.3.2 Design of Graded Bund

Graded bund is designed based on 1h rainfall intensity for desired recurrence interval. In general, a grade of 0.2 to 0.3% is provided in graded channel. In graded bund free board of 15 to 20% of desired depth is provided.

Recommended Dimension

Height of bund ≤ 45 cm

Top width = 30 to 90 cm

Velocity of runoff should be less than critical velocity.

Table 24.1 Recommended side slope for graded bund (Source: Das,2002)

Type of soil	Side slope (horizontal : vertical)
Clayey	1 : 1
Loamy	1.5 : 1
Sandy	2 : 1

Table 24.2 Recommended seepage line slope for graded bund (Das, 2002)

Type of soil	Seepage line slope (horizontal : vertical)
Clayey	3 : 1
Sandy loam	5 : 1
Sandy	6 : 1

(1) Calculation of Vertical Interval (VI) and Horizontal Interval (HI)

For medium to high rainfall areas:

$$VI = 0.1s + 0.6 \quad (m)$$

$$and \quad \frac{s}{100} = \frac{VI}{HI}$$

$$then, \quad HI = \frac{VI \times 100}{s} \quad (m)$$

Where,

V.I = Vertical interval, m

H.I = Horizontal interval, m

s = Original land slope, %

(2) Calculation of Peak Runoff Rate:

$$Q_P = \frac{CIA}{360} \quad \left(\frac{m^3}{s}\right) \qquad by\ Rational\ formula$$

Where,

Q_P = Peak runoff rate (m³/s)

C = Runoff coefficient

I = Rainfall intensity (mm/h) for duration equal to time of concentration.

$$t_c = 0.0195 \left(\frac{L}{\sqrt{S}}\right)^{0.77} \qquad in\ minute$$

Where,

t_c = Time of concentration (min)

L = Length of water flow = (length of bund + distance between two bunds) in (m)

S = H/L = gradient or slope causing water flow

H = Elevation difference causing water flow

= (elevation difference causing length of bund + elevation difference of land)

= (L X g + HI X s)   (m)

g = grade of channel (%)

A= Drainage area (ha)

= (L X HI)

(3) Calculation of Discharge Capacity of Graded Bund
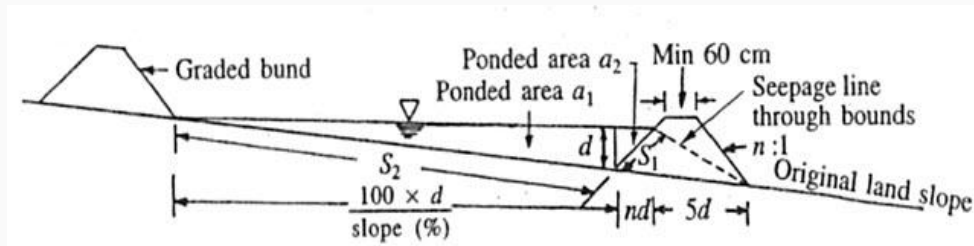
Fig. 24.4. Design layout of graded bund. (Source: Das, 2002)

From the design layout of contour bund (Fig. 24.4),

$$Ponded\ area\ (a_1) = \frac{1}{2} \times \frac{100d}{s} \times d \qquad (m^2)$$

$$Ponded\ area\ (a_2) = \frac{1}{2} \times nd \times d \qquad (m^2)$$

$$Area\ of\ water\ ponded\ behind\ the\ bund = (a_1 + a_2) \qquad (m^2)$$

$$wetted\ perimeter\ of\ ponded\ water\ (P) = (P_1 + P_2) \qquad (m)$$

$$P = \left[\sqrt{\left(\frac{100d}{s}\right)^2 + d^2} + \sqrt{(nd)^2 + d^2}\right] \qquad in\ (m)$$

Where,

d = depth of water stored behind the bund (m)

n:1(H:V) = side slope of the graded bund

5:1 (H: V) = Seepage line slope of the bund for sandy loam soil

$$\text{Hydraulic radius } (R) = \frac{A}{P} \quad (m)$$

$$\text{Mean velocity}(v) = \frac{1}{n} \times R^{\frac{2}{3}} \times g^{\frac{1}{2}} \quad in \left(\frac{m}{s}\right) \qquad by\ Mannings\ equation$$

where,

n = Manning's roughness coefficient

$$\text{Discharge capacity}(Q) = (a_1 + a_2) \times v \quad in \left(\frac{m^3}{s}\right)$$

$$if \ Q > Q_P \quad then\ the\ design\ is\ proper$$

(4) Calculation of Bund Dimension

$$\text{Total height of the bund }(H) = (d + 20\%\ of\ d\ as\ freeboard) \quad (m)$$

$$\text{Base width}(B) = (nd + 5d) \quad (m)$$

$$\text{Top width}(T) = (B - 2nH) \quad (m)$$

(5) Calculation of Earth Work due to Bunding

$$\text{Lengh of contour bund per ha }(L) = \frac{10^4}{HI}$$

$$\text{Earthwork per ha} = cross\ sectional\ area\ of\ bund \times length\ per\ ha$$

$$= \left[\frac{1}{2} \times (B + T) \times H\right] \times L \qquad \left(\frac{m^3}{ha}\right)$$

24.3.3 Bund Construction

In India, construction of bund is done by manual labour, but bullock-drawn buck scrapers, tractor plough, tractor pulled grade terraces, bulldozers and motor graders are also popular.

Lesson 25 Grassed Waterways

25.1 Introduction

Vegetated drainage channels are also called grassed waterways, or vegetated waterways. Such types of channels are either naturally formed or constructed as water courses and planted with grasses. These channels are used for the carrying excess runoff from crop land safely without scouring the channel beds and sides towards the outlets, which may be rivers, reservoirs, streams etc. The vegetated outlets are constructed prior to the construction of terraces, bunds, etc. because grasses take time to establish on the channel bed. Generally, it is recommended that there should be a gap of one year between the construction of grassed water ways and the construction of terraces so that the grasses can be established during the intervening rainy season. Fig. 25.1 shows the grassed waterways.
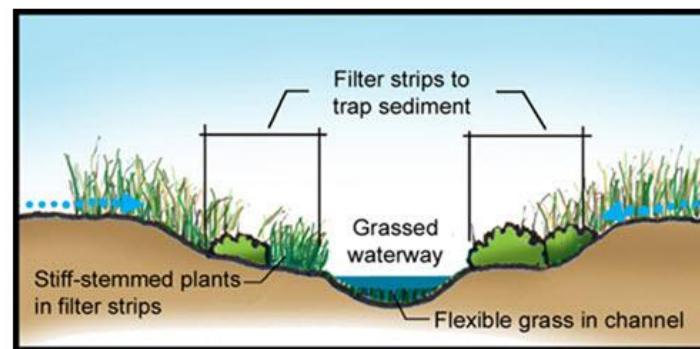
Fig. 25.1. Vegetated waterways (sectional view). (Source: https://www. nac.unl.edu)

25.2 Factors Affecting the Shape of Waterways

 The shapes of grassed waterways are of three types:

(1) Trapezoidal

(2) Triangular

(3) Parabolic

Different shapes of grassed waterways are illustrated in fig. 25.2.
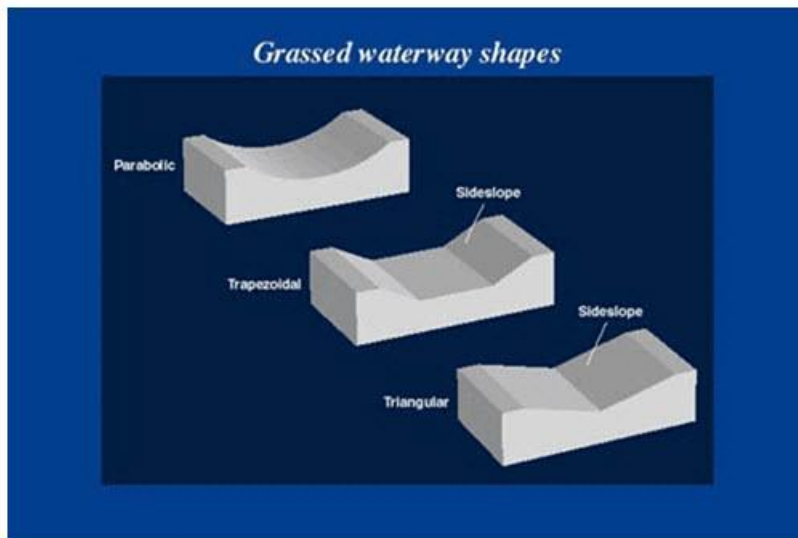
Fig. 25.2. Grassed waterways shapes. (Source: https: //www. www.thisland.illinois.edu)

A parabolic shaped waterway represents a natural channel. In normal course of water flow, the trapezoidal and triangular sections become parabolic in shape due to deposition of sediments over the channel section and bank erosion. At some places earthwork is also not necessary to construct the parabolic shape waterways, only construction of boundaries is needed to define them. The factors that affect the selection of shape of waterways are:

(a) Construction equipment availability

(b) Velocity of flow

(c) Grade of the waterway

(d) The type of grass cover

(a) Construction Equipment Availability

The equipment available for construction of the waterway is one of the main factors. Trapezoidal shaped channel can easily be constructed with the blade type machines provided that the design bottom width of the channel is greater than the minimum width of the cut of the equipment. If the design bottom width of the trapezoidal channel is narrower than the width of the mower swath, then construction is not possible, because neither equipment can move nor desired width of the waterway can be achieved. Similarly, triangular and parabolic shaped channel with side slope of 4:1 or flatter can easily be constructed by using suitable equipment. However, from construction point of view, the trapezoidal cross section can easily be constructed and widely used where the waterway is artificially constructed as terrace outlets along the boundary line. Trapezoidal and triangular cross-section of channel, after some time, is liable to take the form of parabolic section either due to siltation at the bottom or due to scouring of the soil from its bottom and sides. That is why parabolic shape of grassed waterway is generally considered as most economical and also a more stable cross section.

(b) Velocity of Flow:

The permissible flow velocity in the grassed waterway depends upon the type and condition of vegetation and its density to resist the erosion. A uniform vegetative cover in the waterway is important to provide a better channel stability and also to decide the permissible flow velocity. Permissible velocity in grassed waterways varies according to the vegetative growth. The approximate values of permissible flow velocity for different grassed cover are given as:

Permissible Velocity (m/s)	Cover Condition
0.9 to 1.2	Sparse grass cover
1.5 to 1.8	Good grass cover
2.0 to 2.5	Sod of excellent cover

However, for an average condition of grassed cover and channel section, a flow velocity from 1.5 to 2.0 m/s is used for design purposes. In grassed waterways, the average flow velocity is always higher than the actual velocity near the bed, as surface roughness is greater.

(c) Grade of the Waterway

Normally, a channel grade of approximately 5% is recommended for vegetated waterways. A grade of more than 10% is not recommended, as it is likely to become erosive. Vegetated waterways are generally constructed along the direction of the slope.

(d) Grass Cover

The grass cover increases the factor of roughness which reduces the velocity of flow and the channel hydraulic capacity, and along with it, the velocity is made safe (non-erosive) for the runoff to pass through the channel. The value of Manning's roughness factor (n) is not constant for any given species of grass, but varies with the depth and the velocity of flow and the submergence level of grass. When the depth of flow is less, the water seeps through the stems of the grass, which reduces the flow velocity considerably as the resistance to the flow is very high with a high value of n.

25.3 Design of Grassed Waterways

In cases, where the shape of the waterway, the carrying capacity, and the slope of the bed are known, the procedure for the design of the channel parameters comprises of the following steps. This procedure is an iterative one.

Step 1: Assume the value of flow depth and calculate the channel cross sectional area (A), wetted perimeter (P), hydraulic radius (R) and top width (T):

For trapezoidal channel section (Fig. 25.3),
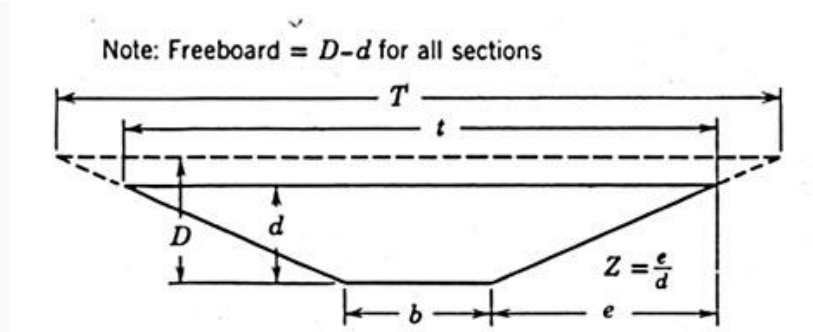
Fig. 25.3. Trapezoidal grassed waterways. (Source: Schwab et al., 1993)

$Cross\ sectional\ area(A) = bd + Zd^2 \qquad (m^2)$

$Wetted\ perimeter(P) = b + 2d\sqrt{Z^2 + 1} \qquad (m)$

$Hydraulic\ radius(R) = \dfrac{A}{P} \qquad (m)$

$Top\ width(t) = b + 2dZ \qquad (m)$

Where,

b = bottom width (m)

d = channel depth (m)

Z = e/d =side slope (horizontal: vertical) of trapezoidal channel

For Triangular channel section (Fig. 25.4),
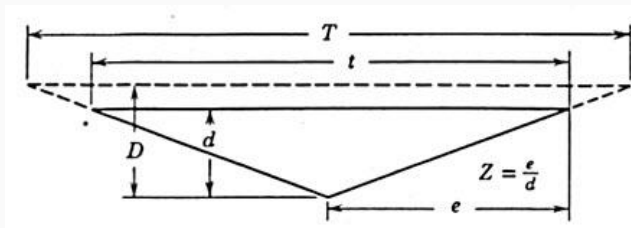
Fig. 25.4. Triangular grassed waterways. (Source: Schwab et al., 1993)

$Cross\ sectional\ area(A) = Zd^2 \qquad (m^2)$

$Wetted\ perimetre(P) = 2d\sqrt{Z^2 + 1} \qquad (m)$

$Hydraulic\ radius(R) = \dfrac{A}{P} \qquad (m)$

$Top\ width(t) = 2dZ \qquad (m)$

Where,

d = depth of channel (m)

For parabolic channel section (fig. 25.5),
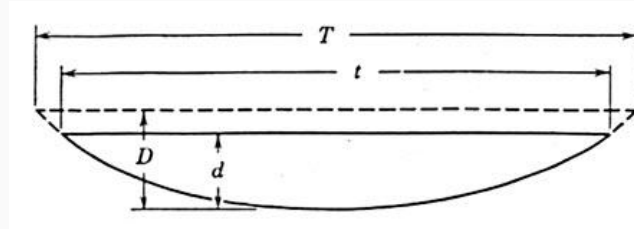
Fig. 25.5. Parabolic grassed waterways. (Source: Schwab et al., 1993)

$$Cross\ aectional\ area(A) = \frac{2}{3}td \quad (m^2)$$

$$Wetted\ perimetre(P) = t + \frac{8d^2}{3t} \quad (m)$$

$$Hydraulic\ radius(R) = \frac{A}{P} \quad (m)$$

$$Top\ width\ (t) = \frac{A}{0.67d} \quad (m)$$

Where,

d = depth of channel section (m)

Step 2: Determine the mean velocity of flow by using manning's formula which states that

$$v = \frac{R^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \quad \left(\frac{m}{s}\right)$$

Where,

R= hydraulic radius of the channel section (m)

S = channel grade

n = Manning's roughness co-efficient (for vegetated waterways, n= 0.04)

Step 3: Determine the discharge rate Q = Av   (m³/s) through the channel.

Step 4: Check if the velocity is safe, and the carrying capacity of the channel is within the permissible range.

Step 5: If it is observed that the velocity is unsafe, and the carrying capacity is not within the permissible range, and then repeat the process with another set of assumed value in step (1), till the carrying capacity is found to be within the permissible range.

Step 6: A free board of 15 cm is then added to the assuming channel depth as

$$Channel\ depth(D) = (d + 0.15) \quad (m)$$

$$Channel\ top\ width\ after\ adding\ free\ board(T) = \frac{D}{d}t \quad (m)$$

Lesson 26 Retaining Wall

26.1 Introduction

Retaining wall is constructed to maintain unequal level of ground surface on both its sides (i.e. back and front) or to support a soil mass. From the soil conservation point of view, the retaining wall is defined as a wall built to retain earth or water behind it. Its constructional feature mainly consists of base, toe, stem etc. The base of the wall is kept wider than the top to adjust the increase of pressure towards base of structure. Fig. 26.1 shows the retaining wall.

Fig. 26.1. Retaining wall. (Source: https://www.langerlandscapes.com)

In many earth work activities, there is excess soil that needs to be disposed safely. Canal construction, dam and reservoir construction, tunneling to convey water from the reservoir/barrage to the power house; generate considerable excess earth, which needs to be safely disposed off such that they do not fall back into an adjoining stream or river. In hilly terrains particularly, vast expanse of flat ground is not available to thinly spread the excess earth. The dug out earth is to be accommodated over smaller areas. This makes it prone to slide down. To avoid this, retaining walls are invariably constructed.

26.2 Types of Retaining Wall

The various types of retaining wall are given as below:

1. Masonry type   2. Semi-gravity type

3. Cantilever type   4. Counterfort type, and

5. Buttressed wall

Fig 26.2 shows the different types of retaining wall.

Fig. 26.2. Types of retaining wall. (Source: https://www.concretenetwork.com)
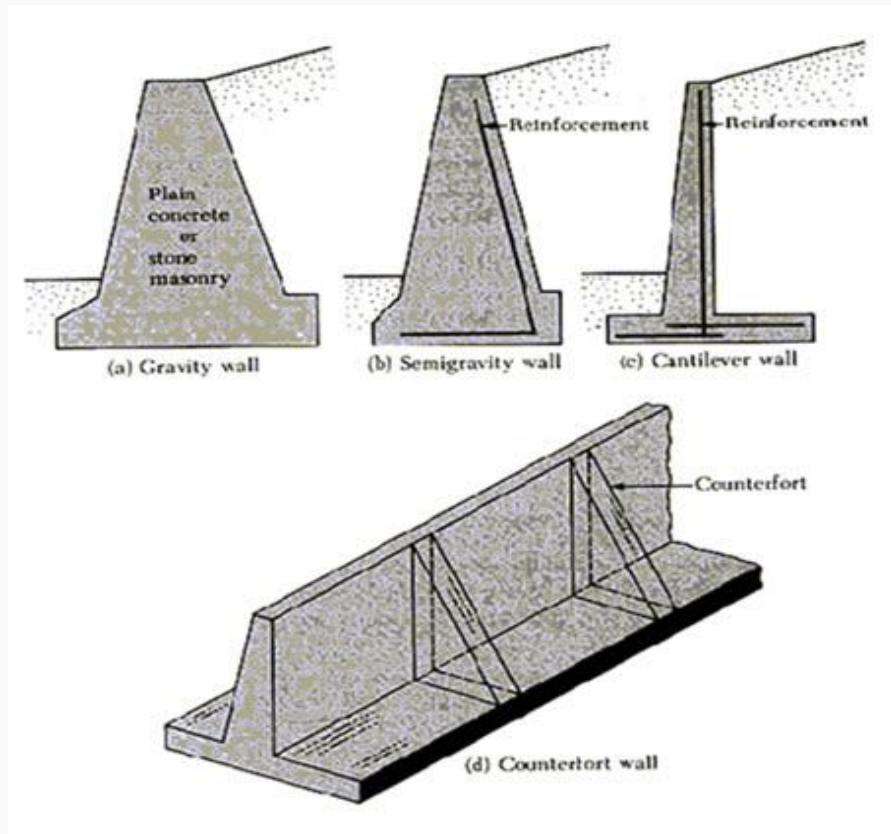
1. Masonry Type

Retaining walls are generally masonry structures. These walls are constructed in between two types of ground surfaces, such as water on one side and land on the other, at different elevations on either side. There may also be soil on both the sides but at different elevations. The material which is supported by the wall is known as the backfill. The surface of the backfill material may be horizontal or inclined. The position of these fill above a horizontal plane, at the top level of the wall is called surcharge, and the angle of inclination of the backfill with the horizontal plane is called the angle of surcharge. Retaining walls constructed to retain water on one side, are also called masonry dams.

Two types of forces act on these types of structures, they are vertical and lateral. The vertical forces are due to self-weight of the structure, and the lateral forces are due to the pressure of wind, earthquake, earth material or water. The masonry structures are designed, such that the shearing action due to the tangential force on the masonry at any level is not greater than the natural friction between any two types of masonry materials. The stability of the structures depends on its self-weight. Therefore, the dimensions of the structures are so designed that the structure remains stable under lateral forces.

The general conditions for the stability of the structure are that there should be no tension across the wall cross section (because, non-reinforced masonry is weak in tension), the maximum compressive stress should be within the limit of safe stress for the material, the

shear force should not be greater than the natural friction between the masonry, and the restoring moment should be greater than the overturning moment.

2. Semi-Gravity Type

This type of retaining wall requires a wider toe to increase the base width of the wall, which causes a major role to prevent the development of tension in the retaining wall. In addition, semi-gravity type retaining wall also needs a fairly heavy section of stem. However, by providing the reinforcement in toe and stem, a heavy section of the wall can be reduced in size and made relatively lighter.

3. Cantilever Type

This type of retaining wall consists of a base slab and a vertical slab, which are joined together in a monolith construction. The front portion of the base slab is termed as toe and rear is known as heel. All these components are designed as cantilever. Sometimes to prevent the wall against sliding, a vertical downward projection known as a key is also provided to its base. It increases the resistance of the wall. The position of the key can be fixed at the following points of the base:

(a) Near the toe

(b) Near the heel

(c) Middle of the base

4. Counterfort Type

The cantilever type retaining walls are economical up to the height of 6m only. When the height exceeds 6 m, counterfort type of retaining wall is preferred for construction. The construction of these types of retaining walls can be made more economical by making the stem and heel as a continuous slab over the counterforts. However, to construct this retaining wall additional amounts of concrete reinforcement and framework are required for constructing the counterforts as an additional part of the wall.

5. Buttressed Wall

Buttressed walls are similar in constructional feature to that of counterfort type retaining walls. The only difference is that the buttressed wall has counterforts in front of the wall, while in the other it is not so. Due to this reason, it is named as buttressed wall. In this wall, the projection of the heel is too small. As a result, the backfill contributes very little stability to the wall and therefore, buttressed retaining walls are rarely used.

26.3 Design of Retaining Wall

The wall is predominantly subjected to the following two forces:

(i) Weight of the wall, acting vertically downward

(ii) Horizontal pressure due to earth materials (or water), acting at a distance of one third height of the retaining wall, from the base.

For making the analysis of above two forces, acting on the wall, let the retaining wall has trapezoidal cross section as shown in Fig 26.3, with 'a' as the top width, b as the width and H as the height.
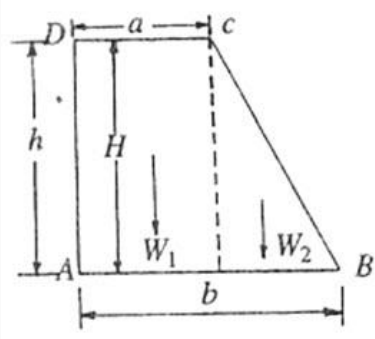
Fig. 26.3. Masonry retaining wall having trapezoidal cross section. (Source: Das, Ghanshyam, 2002)

If soil is filled behind it up to the full height of the wall, (i.e. h=H) then the weight of retaining wall and horizontal pressure due to earth fill are given as follows.

(i) Weight of Retaining Wall

It is given by

$$W = \frac{(a+b)}{2} H \times \lambda r \qquad (kg/m) \qquad \qquad (26.1)$$

Where,

W= weight of the retaining wall (kg/m)

H = height of the wall (m)

The weight of retaining wall acts at a distance 'x' from the vertical face of the wall. The value of 'x' computed following the equation

$$x = \frac{a^2 + b^2 + ab}{3(a+b)} \qquad (m) \qquad \qquad (26.2)$$

(ii) Horizontal Pressure due to Earth Fill

The distribution of horizontal pressure on retaining wall is similar to that of retaining dam i.e. in triangular form, but in case of retaining wall the maximum pressure exerted by the earth fill is somewhat different. It is given by the following expression:

$$P = \frac{\lambda_e h^2}{2}\left(\frac{1 - sin\phi}{1 + sin\phi}\right) \quad (kg/m) \qquad\qquad (26.3)$$

Where,

P= horizontal pressure acting at a distance h/3 from the base of r, wall (kg/m).

Φ = internal frictional angle of the soil (degree)

Maximum and Minimum Stress

Referring to Fig. 26.4, let R be the resultant force of weight of retaining wall (W) and the horizontal pressure (P), acting at a distance Z from point A.
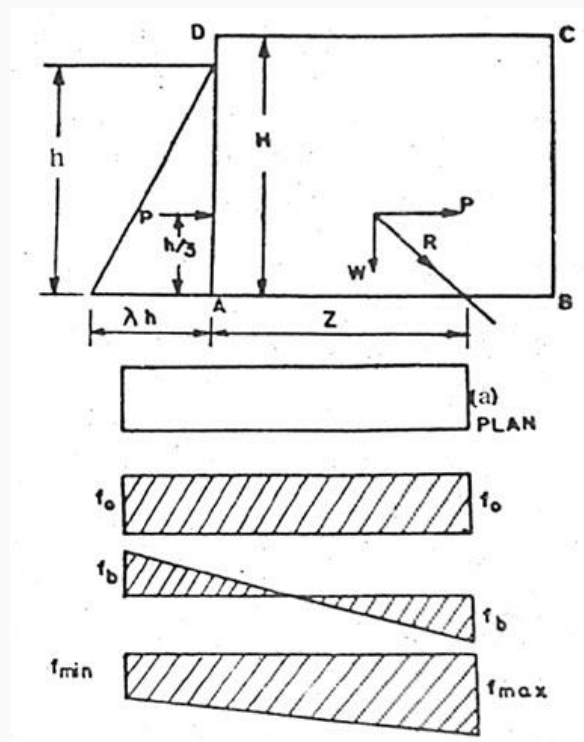
Fig. 26.4. Various forces acting on the retaining wall. (Source: Suresh, 2002)

Now, taking the moment of all forces acting on retaining wall, about A, we have,

$$W\frac{b}{2} + P\frac{h}{3} = moment\ of\ resultant\ force\ (R)about\ the\ point\ A\ in\ (kg)$$

The moment of R about point A is zero, because its line of the action passes through point A.

Thus, $W\frac{b}{2} + P\frac{h}{3} = WZ$

or, $Z = \frac{b}{2} + \frac{P}{W} \times \frac{h}{3}$ (m) (26.4)

Eccentricity (e) of weight (W) at the base $= \left(Z - \frac{b}{2}\right)$ $in\ (m)$

Direct stress on the base of retaining wall $(f_o) = W/b$ (kg/m^2)

Bending moment at the base $= W.e$ in (kg)

Modulus of section $= \frac{b^2}{6}$ (m^2)

Bending stress $(f_b) = \frac{6We}{b^2}$ (kg/m^2)

Maximum stress (f_{max}) at point B = Direct stress on base (f_o) +Bending stress (f_b)

$f_{max} = \frac{W}{b}\left(1 + \frac{6e}{b}\right)$ (kg/m^2) (26.5)

Similarly,

$f_{min} = \frac{W}{B}\left(1 - \frac{6e}{b}\right)$ $\left(\frac{kg}{m^2}\right)$ (26.6)

The bending moment of the wall is developed at its base, due to horizontal pressure caused by the earth fill. This tends to shift the line of action of weight (W) of the retaining wall from the center of the base to right side, at a distance Z from the vertical face. In this condition, the eccentricity (e) at the base is equal to. Since maximum stress occurs at point B and minimum at point A, the nature of these stresses will be compressive so long as the values of the stresses are positive. The maximum stress will always be positive, which indicates the stress to be of compressive in nature. The minimum stress may not be always positive, it can be negative also. The negative value of stress indicates to be of tensile in nature. The tensile stress developed in masonry retaining wall, causes failure. It must be avoided. To avoid the possibilities of development of tension in retaining wall, the value of e should always be less than b/6, which can be obtained by equating the equation of minimum stress equals to zero. That is:

$$f_{min} = \frac{W}{b}\left(1 - \frac{6e}{b}\right) = 0$$

or

$$e = \frac{b}{6}$$

The above equation states that, if the value of e is less than b/6, the f_{min} will be compressive in nature and when e is equal to b/6, the f_{min} will be zero. But when the value of e exceeds b/6, then minimum stress is tensile in nature. Thus, to avoid the possibilities of development of tension in masonry retaining wall, the eccentricity should always be less than b/6 or at most it should be equal to b/6.

Lesson 27 Culverts

27.1 Introduction

Culvert is a structure constructed to link a pathway and is used to pass flowing water underneath and across a road (as illustrated in Fig. 27.1 and 27.2), a railway line, etc, simultaneously maintaining the movement on the road, the rail or other traffic. Sometimes, a culvert may be constructed to cross over a natural depression. Culverts are made of different materials like steel, polyvinyl chloride, concrete and wood, with a suitable combination of some of them. Concrete comes in many shapes and sizes, including round, elliptical, flat-bottomed, pear shaped, and box. They vary from small drainage culverts on highways and driveways to large diameter structures. Long and wide culverts are known as bridges and they require rigorous construction methods. Very small culverts, as are required for movement of humans and cattle in a farm, may be made with a suitable diameter strong pipe laid at the bottom along the water flow direction. The pipe is covered by earth. However, on such a culvert in a farm, the earth cover is replaced by reinforced concrete slab with a required span and width, erected on piers, if movement of farm machinery is involved.

A culvert is defined as the following:

- A structure that is usually designed hydraulically to take advantage of submergence to increase hydraulic capacity.

- A structure used to convey surface runoff through embankments.

- A structure, as distinguished from bridges, that is usually covered with embankment and is composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert.

- A structure that is about 6 meter or less in centerline span width between extreme ends of openings for multiple boxes. However, a structure designed hydraulically as a culvert is treated in this Chapter, regardless of its span.

Some of the basic concepts and definitions that are commonly used in the hydraulic design and installation of culvert are discussed here.

Fig. 27.1. Culverts for stream crossing.
**(Source: http://water.epa.gov/polwaste/nps/urban/upload/2003_07_24_NPS_unpavedroads_
ch3.pdf)**

Fig. 27.2. Bridge culvert.
(Source: http://www.env.gov.nl.ca/env/waterres/regulations/appforms/chapter5.pdf)

27.2 Types of Culverts

The types of culvert are (as illustrated in Fig. 27.3):

- **Pipe Culvert: Single or Multiple**

The Pipe culvert is used for very small drainage works, passing through the embankment of road or railway. It consists of one or more pipes placed side by side. These are made of smooth steel, corrugated metal or concrete materials. The pipe culvert ranges from 30 to 200 cm in diameter and is the cheapest among others. The primary purpose is to pass the water under roads. For the high stream banks round culverts are best suited.

- **Pipe Culvert: Arch Single or Multiple**

It is suitable for large waterways and provides low clearance. At low flows it provides greater hydraulic advantage to fishes to move and requires less road fill.

- **Box Culvert: Single or Multiple**

Box culverts are preferred for construction, especially in loose soil condition and for a larger span. During brief runoff periods, a box culvert is used to transmit water. It can have artificial floor such as concrete. This provides more room for wildlife than the large pipe culverts. Reinforced concrete is used for box culverts. The design of this culvert is based on the continuous beam theory. It requires a good and strong foundation to avoid uneven sinking and the resulting damage to the culvert.

- **Bridge Culvert**

Bridge size culverts are defined as structures that have an equivalent diameter of around 1500 mm or above. This also includes multiple culverts with an equivalent diameter of around 1500 mm or greater.

- **Arch Culvert**

The pipe arch culvert is a round culvert reshaped to allow a lower profile while maintaining similar flow characteristics. When installed with a shallow cover, it works very well. Reinforced concrete, corrugated metals or stone masonry are the materials used for the pipe arch culverts.
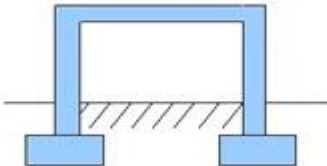
Fig. 27.3. Common Culvert Types. (Source: http://www.aboutcivil.org/culverts-and-its-types.html)

Maintenance of Culvert

Proper maintenance of a culvert is essential for its trouble-free functioning and getting the best performance out of it. A culvert may be damaged and rendered non-functional if loads heavier than that for which the culvert was designed are allowed to pass over; soil erosion at the piers or at the banks, choked water way, etc. To ensure these, the interior of the culvert (i.e., the water way) should be clean always, by removing debris and foreign materials from it. Care and suitable action should be taken such that large vegetation does not grow in the area around culvert, especially on an embankment. Any structural damage, if detected, should be addressed for rectification/repair immediately. As the water flow path dimensions are usually larger at the culvert, farm animals in India are known to gather there not only to drink water but also to dip in the water in summers. This is a common cause of damage to the culverts in agricultural areas and suitable protection mechanism is to be thought and implemented.

27.3 Design of Culverts

27.3.1 Required Design Information

The hydraulic design of a culvert essentially consists of an analysis of the required performance of the culvert to convey flow across the path way. The designer must select a design flood frequency, estimate the design discharge for that frequency, and set an allowable headwater elevation based on the selected design flood and headwater considerations. These criteria are typically dictated by local requirements and certain standards exist in the civil engineering design books on bridges and culverts. The culvert size and type can be selected after the design discharge, controlling design headwater, slope, tailwater, and allowable outlet velocity have been determined.

The design of a culvert includes determination of the following:

- Impacts of various culvert sizes and dimensions on upstream and downstream flood risks, including the implications of embankment overtopping.

- How will the proposed culvert/embankment fit into the relevant major drainage way master plan, and are there multipurpose objectives that should be satisfied?

- Alignment, grade, and length of culvert.

- Size, type, end treatment, headwater, and outlet velocity.

- Amount and type of cover.

- Public safety issues, including the key question of whether or not to include a safety/debris rack

- Pipe material.

- Type of coating (if required).

- Need for fish passage measures, in specialized cases.

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- Need for protective measures against abrasion and corrosion.

- Need for specially designed inlets or outlets.

- Structural and geotechnical considerations,

27.3.2 Culvert End Treatments

End structures (as shown in Fig. 27.4) are attached to end of culvert barrel to reduce erosion, inhibit seepage, retain the fill, and improve hydraulic characteristics.

Possible Choices:

- Projecting

- Mitered

- Flared-end Section

- Headwalls and Wingwalls
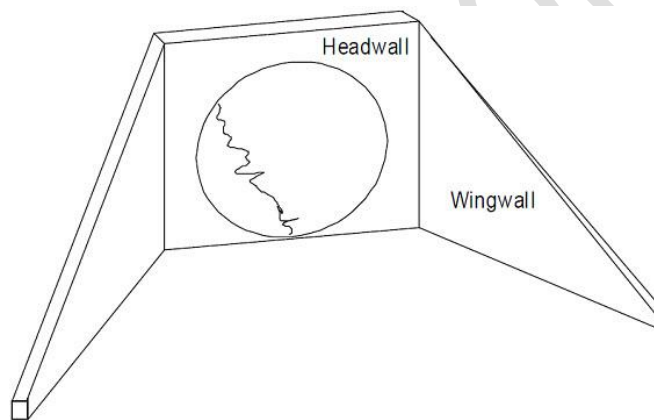
Fig. 27.4. Culvert End Treatments.
(Source: https://engineering.purdue.edu/~abe527/lectures/culvertdesign.pdf)

27.3.3 Hydraulic Design Considerations

1. Design Flood Discharge

- Watershed characteristics

- Design flood frequency or return interval

- All designs should be evaluated for flood discharges greater than the design flood

2. Headwater Elevation - check upstream water surface elevation

3. Tailwater - check that outlet will not be submerged

4. Outlet Velocity - usually controlled by barrel slope and roughness

27.3.4 Terminology

(1) Headwater (HW) – Depth from the culvert inlet invert to the energy grade line

(EGL). If the approach velocity head is small then HW is approximately same as the upstream water depth above the invert.

(2) Tailwater (TW) – Depth of water on the downstream side of the culvert. The TW depends on the flow rate and hydraulic conditions downstream of the culvert.

27.3.5 Culvert Design Approaches

1. Design based on design flood discharge and allowable headwater elevation.

Tailwater conditions are to be checked to verify the design.

2. Flood routing through the culvert. Data inputs include

- an inflow hydrograph

- an elevation versus storage relationship

- an elevation versus discharge relationship (rating curve)

27.3.6 Types of Flow Control

1. Inlet Control - flow capacity is controlled at the entrance by the depth of headwater and entrance geometry, including the barrel shape, cross sectional area and the inlet edge.

2. Outlet Control - hydraulic performance controlled by all factors associated with Inlet Control, and additionally include culvert length, roughness and tailwater depth.

27.3.8 Culvert Hydraulics - Inlet Control

Two possible conditions:

(1) Unsubmerged - steep culvert invert and headwater not sufficient to submerge inlet. Culvert inlet acts effectively like a weir. The culvert capacity is given as:

$Q = C_w B (HW)^{3/2}$

Where, B = width of weir crest

A weir coefficient $C_w = 3.0$ may be assumed for initial calculations.

(2) Submerged - headwater submerges top of culvert inlet but the barrel does not necessarily flow full. Culvert inlet acts like an orifice or sluice gate.

$$Q = C_d A \sqrt{2 g (HW - b/2)}$$

Where, b = culvert height

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HW – b/2 = head on culvert measured from barrel centerline

Orifice discharge coefficient, C_d, varies with head on the culvert, culvert type, and entrance geometry. Nomographs and computer programs are usually used for design. For initial calculations a value $C_d = 0.60$ may be used.

27.3.9 Culvert Hydraulics - Outlet Control

Outlet control will govern if the headwater is deep enough, the culvert slope is sufficiently flat, and the culvert is sufficiently long.

Three possible flow conditions:

1. Both inlet and outlet submerged, with culvert flowing full.

2. Inlet is submerged but the tailwater does not submerge the outlet. In this case the barrel is full over only part of its length.

3. Neither the headwater nor tailwater depths are sufficient for submergence.

Culvert capacity determined from energy equation:

$$HW \; S_o \; L \; \square TW \; h_e \; h_f \; h_v$$

Where,

HW - TW = total energy head loss (m)

S_o = Culvert slop

L = Pipe length

h_e = entrance head loss (m)

h_f = friction losses (m)

h_v = velocity head (m)

Entrance Head Loss, h_e

$$h_e = K_e \frac{v^2}{g}$$

Culvert Entrance Loss Coefficients,	Ke
Pipe with projecting square-edged entrance	0.5
Pipe metered to conform to fill slope	0.7
Box with wing walls at 30º to 75º to barrel	0.4

Friction Losses, h_f

Mannings Equation

$$V = \frac{1.49}{n} R_h^{2/3} S^{1/2}$$

or

$$h_f = 29 \frac{n^2 L}{R_h^{4/3}} \left(\frac{V^2}{2g}\right)$$

Design equation for Case 1:

$$HW = TW \left[K_e + 29 \frac{n^2 L}{R_h^{4/3}} + 1\right] \left(\frac{V^2}{2g}\right) - S_o L$$

Roadway Overtopping

During roadway overtopping, the roadway acts as a weir:

$Q = C_w L (HW_r)^{3/2}$

HWr = upstream depth, measured above roadway crest (m)

27.3.10 Concepts of Culvert Design

- Most culverts operate under downstream control. This means that the hydraulic computations proceed from the downstream to the upstream direction.

- The design discharge and allowable headwater elevation are initially established. Other constraints such as culvert shape, material, aesthetics, etc. are specified.

- Assume a culvert size and check performance assuming both inlet and outlet control. Whichever gives the highest HW elevation controls the hydraulic performance.

- Compare culvert performance with design constraints, and select the smallest (least expensive) size that meets the criteria.

Lesson 28 Temporary Control Structures

28.1 Introduction

Temporary physical and structural measures such as gully reshaping, brushwood dam, protection by sandbag, loose stone barrier, gabion structures and arc-weir check-dams are used to dissipate the energy of runoff and to keep the gully stable. Check-dams are constructed across the gully bed to stop channel bed erosion. By reducing the original gradient of the gully channel, check-dams reduce the velocity and erosive power of runoff. Run-off during peak flow is conveyed safely by check-dams. The structures can be either temporary or permanent. The choice of the measures and extent of their use will depend on the amount of the runoff and the status of the gully; whether young and actively eroding or mature and stabilizing naturally. Good judgment is required in determining what measures to be used that are both economical as well as effective. Consideration should then be given to the ways of stabilizing the gully head, floor and sidewalls.

An effective sediment and erosion control plan should:

- Minimize clearing: use site fingerprinting, buffers and construction phasing.

- Prevent off-site runoff from flowing across bare soils: use perimeter dikes and diversions.

- Stabilize bare soils on the site: use erosion control mats, planting, retaining walls.

- Remove sediment from runoff before it leaves the site: use stabilized construction entrances/exits, silt fences, sediment traps, check dams.

- Plan soil disturbance activities for the dry season.

28.2 Check Dam

A check dam, sometimes known as ditch check, is a barrier constructed across waterways such as open channel, swales, and ditch or drains. Check dams retain water behind them that helps the surrounding soil to remain wet for a longer time after the monsoon season is over. Check dam can either be a temporary or a permanent structure, which is built to retain and maintain the desired groundwater level within the peatland. In this way, it reduces the possibility of ignition of fire in the drying peat as well as prevents any fire from spreading during any hot and dry spell. In the context of fire prevention and control, check dams are specifically installed for the following purposes:-

a) To maintain minimum water level in the forest areas so as to avoid any fire ignition on land surfaces.

b) To maintain high soil moisture levels so as to minimize fire in the forest areas from occurring and spreading especially during prolonged dry and hot season

c) To prevent over-drainage of the peat land which will lead to drying out of the organic materials causing carbon release as well as land subsidence.

d) To conserve as much water as possible during the post-monsoon season that would help to recharge ground water.

28.3 Classification of Check Dam

The check dams are classified as:

(1) Temporary check dam

(a) Brushwood dams

(i) one row or single post brush wood dam

(ii) Double row post brush wood dams.

(b) Semi permanent dams

(i)   Loose rock dam

(ii) Netting dam

(iii) Log check dam

(2) Permanent check dam

(a) Drop Spillway

(b) Drop inlet spillway

(c) Chute spillway

28.4 Durability of Check Dam

Check dams can be built using various types of materials such as earth, sand (loose or in bags), timber (sawn or log), stones/rocks (loose or stacked), or concrete (precast form). In selection of the most appropriate materials to be used as the main components of the check dam structure, designer should take into consideration the following factors:

- Size and dimensions of check dam

- Site conditions (e.g. waterlogged, depth of peats)

- Accessibility of site

- Availability of suitable materials locally

- Designed service life of the structure (short-term, medium term or long-term)

- Cost of construction

Temporary Check Dam

Temporary check-dams, which have a life-span of three to eight years, collect and hold soil and moisture in the bottom of the gully to give vegetation an opportunity to establish. Runoff control structures may be needed to be commissioned in the gully.

28.5 Gully Reshaping and Filling

Gully wall reshaping involves cutting off steep slopes of active gully flanks into gentle slope (maximum at 45% slope), up to two-third of the total depth of the gully and construction of small trenches along contours for re-vegetating slanted part of the gully walls and beds, as illustrated in Fig. 28.1. If the gully is wide and has meandering nature with huge accumulation of runoff flowing down; cut off soils and soil materials can be washed away by runoff water and requires construction of retaining walls, as illustrated in Fig. 28.2, to protect displaced (not yet stabilized) soils and soil materials and newly created sidewalls of the reshaped gully.

Fig. 28.1. Gully reshaping and filling. (Source: https://energypedia.info/images/a/aa/GullyReshapingRevegetation.png)
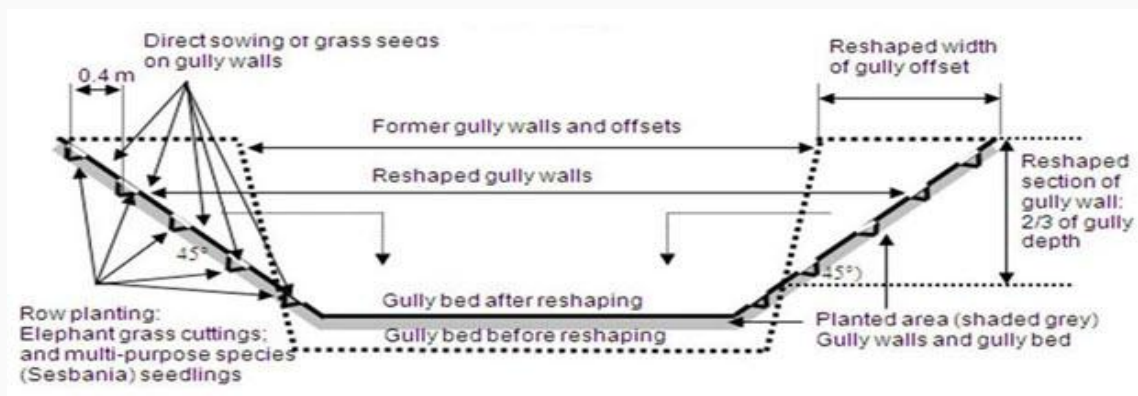
Fig. 28.2. Gully wall reshaping without retention wall. (Source: http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFinal_ENTRO_TBIWRDP.pdf)

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Gullies with very little water flow can be stabilized by filling and shaping; that is, if the surface water is diverted, and livestock are kept out. Steep gully heads and gully banks should be shaped to a gentler slope (about a one-to-one slope). Filling of gullies is applicable only for small discontinuous gullies, in their early stages of development. The filled gully area can be planted and even be used for cultivation. Rills and incipient branch gullies may be filled in by spade, shovel or plough (on cultivated lands).

The practicability of shaping a gully depends on its size and the amount of fill needed to restore the gully to its desired shape. Steep gully sides can be reshaped. Topsoil should be stockpiled and re-spread over exposed areas to ensure the rapid establishment of vegetation. Annual grass and crops such teff, oats or barley can be used to provide a quick cover. It may be possible to temporarily divert water from the battered gully while grass is establishing.

The common practice of filling gullies with rubbish, logs, rocks, branches, twigs and other materials does very little to solve the problem. In most cases, particularly in gullies that carry copious runoff during the monsoon season, it makes the gully worse particularly if the placement and anchorage of those materials is not done properly.

Generally, in the filling and shaping process the following need to be considered:

- The soil should be well compacted

- The filling operation should be done before the rains

- To protect it from erosion, close growing crops should be planted or seeded immediately

- The entire work of shaping and filling should be done in one operation

28.6 Brushwood Check Dam

Brushwood check-dams made up of posts and brushes are placed across the gully, as shown in Fig. 28.3 and 28.4. The main objective of brushwood check-dams is to hold fine materials carried by flowing water in the gully. Small gully heads, no deeper than one meter, can also be stabilized by brushwood checkdams. Brushwood check-dams are temporary structures and should not be used to treat ongoing problems such as concentrated run-off from roads or cultivated fields. They can be employed in connection with land use changes such as reforestation or improved range management until vegetative and slope treatment measures become effective.

The main requirement of temporary gully control structures is that, they must be quick and easy to construct, should be made by using cheap and readily available material in nearby areas.

Fig. 28.3. Brushwood check dam.
(Source: http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFinal_EN
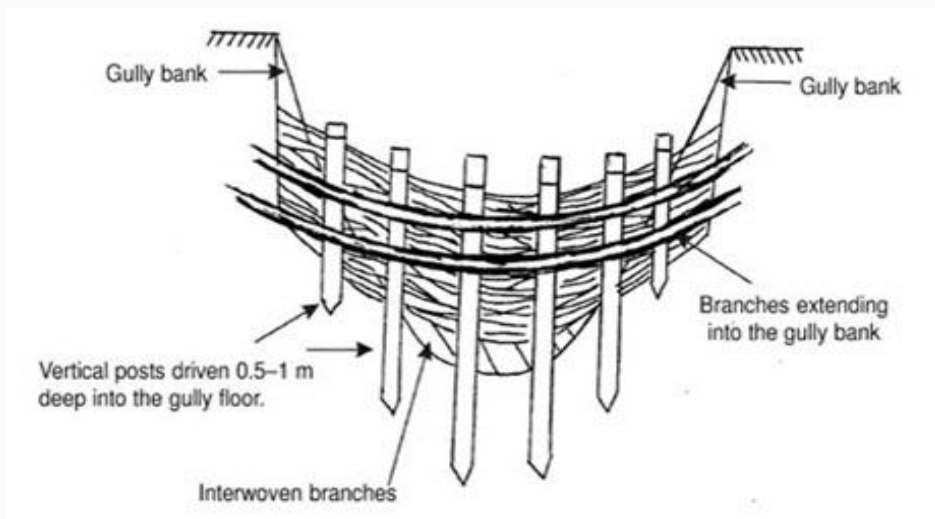**TRO_TBIWRDP.pdf)**

Fig. 28.4. A single row brushwood check-dam front
view. **(Source: http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFin**
al_ENTRO_TBIWRDP.pdf)

In areas where the soil in the gully is deep enough, brushwood check-dams can be used if proper construction is assured. The gradient of the gully channel may vary from 5 to 12 percent, but the gully catchment area should not be as such huge which produces high amount of runoff volume. There are two types of brushwood check-dams: these are single row and double row brush wood check-dams. The type chosen for a particular site depends on the amount and kind of brush available and on the rate and volume of runoff. The maximum height of the dam is one meter from the ground (effective height).

1. Single Row Brushwood Check-dams

These check-dams can be used where the rate of runoff is less than 0.5 m³/sec. The structure is temporary and its durability will depend on the quality of posts used. If possible live posts of willow, popular and other trees should be used (8-10 cm dia). Flexible branches are cut

and woven around the posts. This dam is constructed across the channel or gully with the brush wood materials, laid along the flow of water, keeping the butt ends towards u/s face of the gully, as shown in Fig. 28.5. The brushwood is kept in position by tying to the posts. Before the dam construction is begun, the sides of the gully or channel should be sloped to 1:1 and the gully bed should also be excavated for 15 cm depth along the entire gully width over which brushwood have to be laid. In addition, 15 cm excavation is also done into the bank to give necessary notch capacity.

After excavation, the wooden posts of about 10 cm in diameter are driven in a line across the gully at an interval of 90 cm up to a depth of 75 cm in gully bed. The top of wooden posts should be kept at such a height so as to form a notch of required size. The brushwood is tied from the front line and the other lines are tied using galvanized wire for keeping them in position. The lowest layer of the brushwood must be the longest.
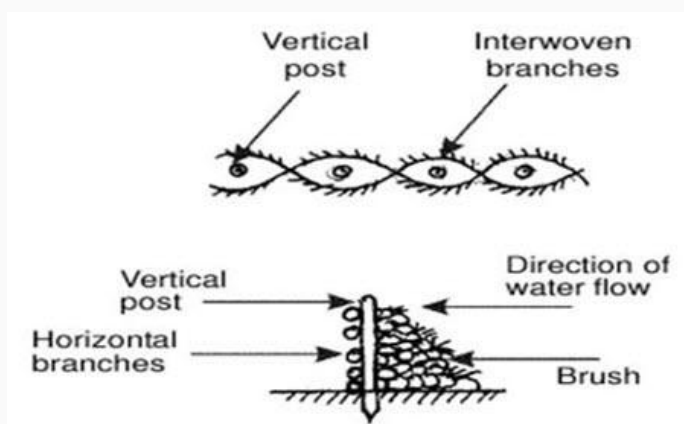
Fig. 28.5. Vertical and side views of single row check-dam.
**(Source: http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFinal_EN
TRO_TBIWRDP.pdf)**

2. Double Row Brushwood Check-Dam

This type of brushwood check-dam is suited where the rate of runoff is less than 1 m³/sec. The construction of the dam starts with an excavation in the floor and into the sides of the gully to a depth of 0.3-0.5 m. Two rows of posts, 5-10 cm in diameter and 1-2 m in length are placed into the holes, across the floor of the gully to a depth of 0.5-0.6 m. The spacing between the posts is 0.5 m. Brushwood or branches are packed between the posts. The height of the posts in the center should not exceed the height of the spillway otherwise the flow will be blocked and water may be forced to move to the gully sides. Fig. 28.6 shows the double row brushwood check dam.
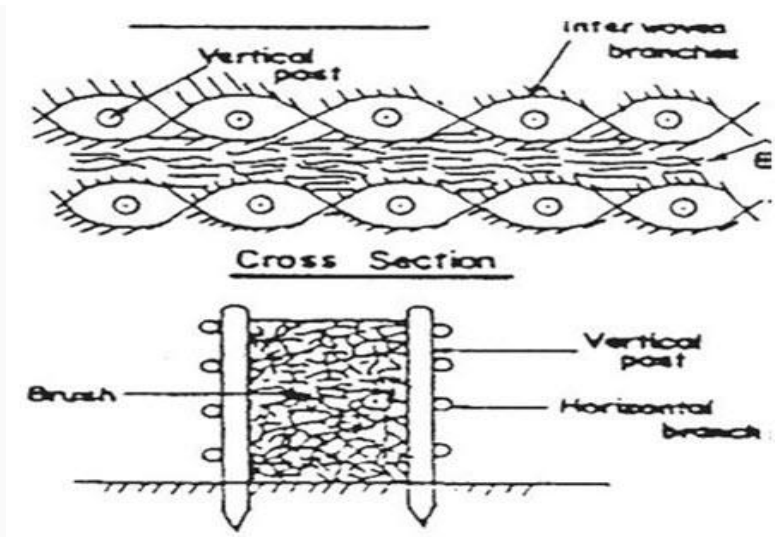
Gulley and Ravine Control Structures

Fig. 28.6. Double row brush wood check-dam.
(Source: http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFinal_ENTRO_TBIWRDP.pdf)

28.7 Specifications for Brushwood Check-dams

- The choice for post brush check-dam must be made after careful examination of material availability in the near vicinity. Otherwise, problem of cutting all the sparse vegetation in the area would bring in undesirable results.

- Brush wood check-dams particularly single rowed ones can be strengthened with bamboo mat or sand filled bags on the upstream part to serve as a shock absorber and to dissipate the runoff energy during pick flows.

- Any tree or shrub species can be used as posts. But the wooden posts should be rot resistant and termite proof. The brushwood must not be very dry and easily breakable.

- To avoid the brushwood being removed by flowing water, it is necessary to fix the brushwood with rope, wire or nail.

- The ends of interlink materials should enter at least 30 cm into the sides of the gully.

- The space behind the brushwood check-dams must be filled with soil to the spillway, if either sand bag or bamboo mat is not used.

- If sprouting species (salix and popular) are selected as posts and interlink materials, brushwood check-dams should be constructed when the soil in the gully is saturated or during the early rainy season.

- If non-sprouting species are used as strips and interlink materials, brushwood check-dams can be constructed during any season

Lesson 29 Control by Semi-permanent Structures

29.1 Loose Rock-fill Dam

This type of check dam is simple in construction and very effective for gully control. These dams are preferred in those areas, where plenty of loose rocks are available nearby the gully. The loose rock-fill dams are constructed with the help of stones. The stones are kept across gully width by wire netting made of fairly stout gauge of galvanized iron wire. The wire netting of about 2 meter or more in width is laid across the gully bed and over it the loose rocks are packed approximately up to half of the width of netting. The other half of netting is wrapped over the stones and laced to the other edge.

Fig. 29.1. Making of loose stones check dam.
(Source: http://www.geoengineer.org/multimedia-virtual/item/282-history-of-rockfill-dam-construction-part-2)

Design and construction specifications of loose stone check-dam

- The foundation of the dam is dug so that the length of the foundation will be more than the length of the spillway.

- The width of the foundation depends upon the reservoir level height.

- The dam should be properly keyed across its base and up the abutments to the crest elevation.

- An adequate spillway should be provided for safe disposal of water.

- An apron of non erodible material should be provided at the base, to dissipate the energy of water falling through the spillway.

- Proper spacing between the successive dams should be ensured

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- The height of the dam should be properly planned

- Stones should be placed such that they interlock easily and form a denser structure. If small stones are to be used they should be placed in the center and the outer surface covered with large stones to strengthen the dams.

- Loose stone check-dams can be strengthened by covering the upstream wall and the crest with bamboo/reed-mat.
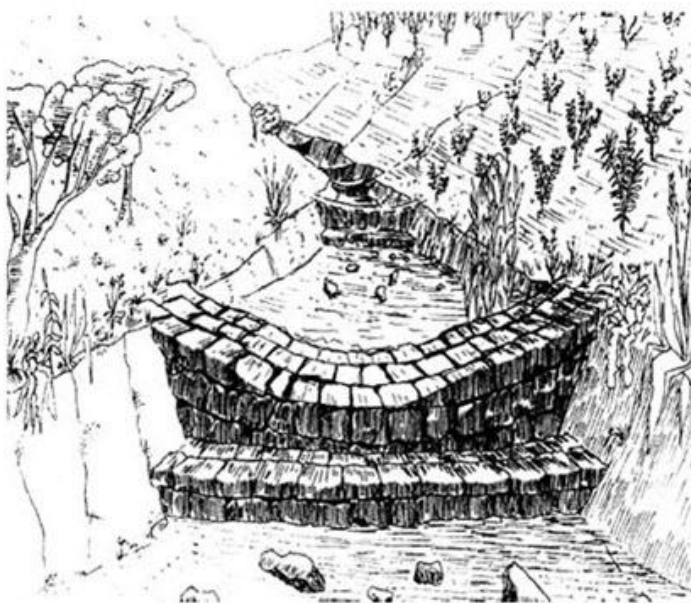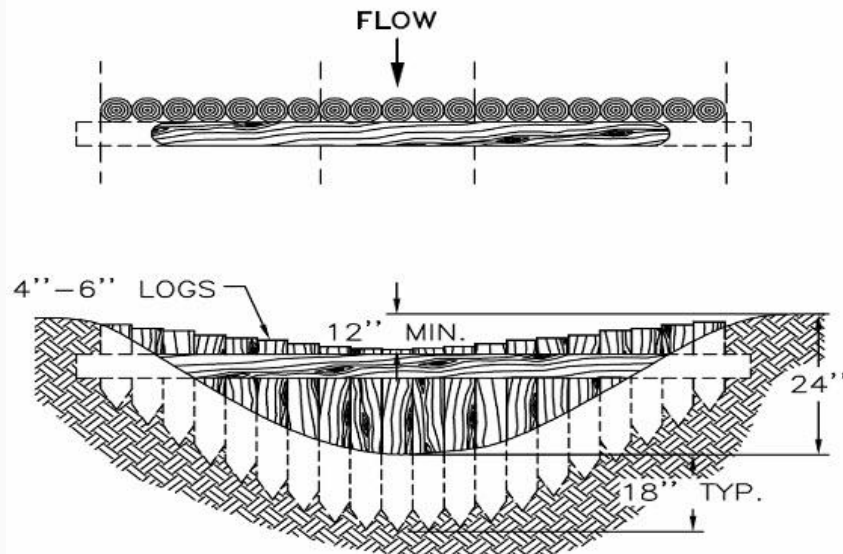

Fig. 29.2. A typical loose stone check-dam.
(Source: http://opcgis.deq.state.ms.us/Erosion_Stormwater_Manual_2ndEd/Volume1/Chap
_4_Sections/4_4/V1_Chap4_4_Runoff_Conveyance_CD.pdf)

29.2 Log Check-dam

When large size timbers are readily available in the nearby area of gully, the log check dams are used for checking the gully. In this dam, the logs are used as brushwood but they make the structures substantially stronger. In the log check dam, two rows of vertical wooden posts are formed by inserting the wooden posts in line with the gully bed and extending up to the sides above the flood level and then logs are packed between the two rows. The vertical posts should be at least 10 cm in diameter and 2 m long. The spacing should be kept about one meter between each row, with the two rows of posts half meter apart. In wide and shallow gullies, it is better to keep all vertical post to a height of 60 cm above the ground surface so that the top of the dam can follow the section of stream bed. If the gully has steep sides, it should have a rectangular notch in the centre but the notch must be large enough to pass whole of runoff. The vertical posts on either sides of notch are responsible for dissipating the kinetic energy of flowing water. Therefore logs should not be swept down by the flow, for which stout posts must be driven to a greater depth than the others.

When the logs are fully packed between the rows of posts, the bottom layer to be sunk below the dam may be checked.

Fig. 29.3. Log Check Dam.
(Source: http://opcgis.deq.state.ms.us/Erosion_Stormwater_Manual_2ndEd/Volume1/Chap
_4_Sections/4_4/V1_Chap4_4_Runoff_Conveyance_CD.pdf)

29.3 Netting Dam

In this dam wire netting is used to form a small check dam. The netting dams are usually located near the top end of the gullies. This dam consists of wooden posts which are driven into the gully bed to support a strip of wire netting and thus, forming a low wall across the gully. The height of dam is kept about 60 cm. The lower edge of the netting is buried into the gully bed. The brush or straw is also piled loosely towards upstream side of the netting wall to form a barrier, which is porous in nature. But it slows down the flow velocity and results in deposition of sediment on the upstream side.

29.4 Geo-Textiles for Gully/Erosion Control

Geotextiles are porous fabrics known in the construction industry as filter fabrics, road rugs, synthetic fabrics, construction fabrics, or simply fabrics. Geotextiles are manufactured by weaving or bonding fibers made from synthetic materials such as polypropelene, polyester, polyethylene, nylon, polyvinyl chloride, glass and various mixtures of these. The uses of geotextiles include separators, reinforcement, filtration and drainage, and erosion control.

Geotextiles can be used for erosion control by using it alone. Geotextiles, when used alone, can be used as matting. Matting's are used to stabilize the flow on channels and swales. Also, matting is used on recently planted slopes to protect seedlings until they become established. Also, matting may be used on tidal or stream banks where moving water is likely to wash out new plantings.

Geotextiles are also used as separators. An example of such a use is geotextile as a separator between riprap and soil. This "sandwiching" prevents the soil from being eroded from beneath the riprap and maintaining the riprap's base.

Fig. 29.4. Mulch geotextiles. (Source: http://coirgreen.wordpress.com/2013/04/03/coirgreen-geotextiles-an-effective-soil-erosion-prevention-method/)

29.5 Sandbag Check-Dam

Sandbag check-dams are made from used jute or polyethylene bags (50 kg) filled with soil/sand. The bags are piled up to a maximum of 3 – 4 layers to form a small check-dam. This cheap technique is particularly useful in areas with insufficient supply of stones for building ordinary check-dams. By erecting sandbag dams large rills or small gullies (finger gullies) can be controlled, while they are not suitable for the treatment of large gullies.

Fig. 29.5. Sandbag check-dam.
(Source: http://www.aquadam.net/Construction/Apple%20Creek-CA%20Dam/apple2.html)

29.6 Gravel-filled Burlap Bags

Gravel-filled burlap bags may be used for temporary check dams in areas of concentrated flow. The burlap bag flaps under the bags is folded in a direction away from the water flow. Gravel bag check dams are constructed such that the crest of the downstream check dam is approximately level with the toe of the upstream check dam. The check dams are installed so

that the side end points are higher than the centerline crest. Erosion caused by high flows around the edges should be corrected immediately.

29.7 Retaining Wall with Bamboo-Mat

In gully rehabilitation scheme, the difficult part is to control the lateral flows which are coming from farm fields, footpaths, degraded grazing areas and other miscellaneous land use types. To protect the lateral flows and hence mass movement and soil sliding/melting from fragile sidewalls of a gully, retaining walls made out of reed/bamboo mat can be installed along the foot of the sidewall. The mat can be strengthened on the lower side by wooden sticks, possibly using vegetative propagating species like popular, willow and indigenous species. "Mini" bundles, with or without pegging, are also employed in small soil and moisture pockets. Arundo donax and Hyparrhenia stems consisting of three to four nodes each proved particularly useful for this purpose. Retaining, bundling and pegging commence with the onset of the rainy season.

Fig. 29.6. Protecting gully sidewall using bamboo-mat retaining wall.
**(Source: http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFinal_EN
TRO_TBIWRDP.pdf)**

29.8 Precast Concrete Stacked Blocks Check-Dam

Stacked precast concrete blocks can also be used for the construction of check dam structures. Some requirements for precast concrete block check dams are:-

i) Proper foundation has to be provided to prevent excessive deformation and bearing capacity failure. If necessary the layer of soft and peat soils should be replaced.

ii) The stacked precast concrete blocks should be stable and designed as mass gravity wall that is able to resist both hydraulic and earth pressures.

iii) The dimensions of each individual precast block are to be decided based on handling as well as stability requirements

iv) The precast blocks should be able to be removed swiftly in case of overtopping and flooding problems.

a) Side View

a) Upstream View

Fig. 29.7 Precast Concrete Stacked Blocks Check Dam Structures. (Source: http://info.water.gov.my/attachments/article/324/GuidelineCheckDams CompleteSet.pdf)

29.9 Locally Available "Organic" Gabion Boxes

"Organic" gabion boxes are made from locally available bamboo and reed strips, which are woven and tied together to form cubic, permeable boxes to be filled with stone. The organic gabions are placed across gully floors, and buttressed downstream for stability. The characteristic of the specific location determines the height and the width of the organic gabion check-dam, and consequently the number and size of gabions to be utilized for.

Consequently, the velocity of the run-off is reduced, and sedimentation creates a favorable atmosphere/ environment for the establishment of permanent biological structures. Accordingly, appropriate vegetative structures are put in place so as to strengthen and finally replace the "organic" gabion that rots over time.

Fig. 29.8. Check-dams constructed out of organic boxes (bamboo and reed mat). (Source: http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFinal_EN TRO_TBIWRDP.pdf)

29.10 Silt Fence

A silt fence is a temporary sediment barrier consisting of fabric stretched across and attached to supporting posts and entrenched into the soil. It is generally installed perpendicular to the flow direction to slow down or stop water and to allow filter/perimeter protection, settling of soil particles, and/or reduce water velocity/erosive forces.

Fig. 29.9. Silt Fence. (Source: http://www.interstatelandscaping.com/Page_4.html)

29.11 Sediment Basin

Semi-permanent to permanent version of the Sediment Trap is constructed by excavation, embankment, or a combination of these to intercept, trap, and retain sediment from runoff while allowing detained runoff to slowly drain, infiltrate, or both. These structures are used for indefinite periods of sediment collection associated with long term disturbance of the earth such as mining, farming, unpaved road drainage, etc. Sediment and runoff storage capacities are often larger than sediment traps, and embankments are usually constructed from more permanent materials such as compacted earth, rock, concrete, etc. Sediment laden runoff can be drained and filtered by perforated pipe, rock filtration, rock dam seepage, infiltration, pumping, or a combination of these.

Fig. 29.10. Sediment Basin.
(Source: http://www.al.nrcs.usda.gov/news/sstories/1109sed_basin_lee.html)

Lesson 30 Control by Permanent Structures

30.1 Spillway

Dams and barrages are constructed to store runoff water from the catchments for its simultaneous and/or subsequent use for hydro power generation, irrigation, drinking water supply, flood control, etc. They are much larger structures constructed across rivers and tributaries than what have been discussed so far as means of gully control measures. Dams and barrages create a reservoir behind them and have a spillway section through which the water in excess of the reservoir capacity is released downstream. The reservoirs need to be protected against uncontrolled sediment deposit in them through erosion control measures adopted in the catchment area. Spillways are also used to flush out some of the sediment deposited in the reservoir. In diversion works, like weirs and barrages, spillways bypass the flow exceeding that which is released into the system like irrigation canals, power canals, feeder canals, link canals etc. Ordinarily, the excess flow is drawn from the top of the pool created by the dam and conveyed downstream through the spillway, back into the same river or to some other drainage Channel. Fig. 30.1 shows spillways in Bhakra dam and Hirakud dam respectively.
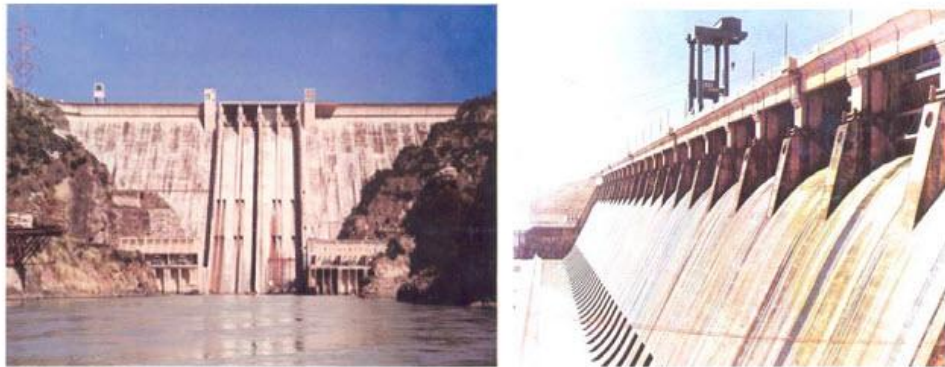
**Fig. 30.1. Spillway in bhakra dam and spillway in hirakud dam.
(Source: http://profskmazumder.com/IT%20PDF/Ref_02.pdf)**

30.2 Components of a Spillway

A spillway generally has the following components

1. Entrance channel

2. Control structure

3. Discharge channel (or waterway)

4. Terminal structure (energy dissipater)

5. Exit channel

However, entrance and exit channels may not be required for some spillways, which one usually comes across in agricultural lands.

1. Entrance Channel

Entrance channels are required in those types of spillways in which the control structure is away from the reservoir. The entrance channel draws water from the reservoir and carries it to the control structure. Entrance channels are not required for spillways which draw water directly from the reservoir.

2. Control Structure

The control structure (also called control) is the most important component of the spillway. It controls the outflow from the reservoir. The control structure is designed such that it does not permit the outflow from the reservoir when the water level is lower than a predetermined level but permits the outflow as soon as the water level rises above that level. Generally the control structure is located at the upstream end of the spillway structure. The control structure usually consists of either an orifice or a weir. In most of the spillways, the control structure is an overflow crest of a weir. The weir may be sharp-crested, board-crested or ogee-shaped.

3. Discharge Channel (or waterway)

The outflow released through the control structure is usually conveyed to the terminal structure through a discharge channel or waterway. Thus the discharge channel conveys the water safely from the control structure to the river downstream. It is also called a conveyance structure. The conveyance structure may have different forms. It is usually the downstream face of an overflow darn for the spillway constructed as an overflow spillway in the body of the dam. It may be in the form of an open channel, a closed conduit placed through or under a dam, or a tunnel excavated through an abutment, depending upon the type of spillway. The discharge channel may have a variety of cross-sections, depending upon the geologic and topographic characteristics of the site and the hydraulic requirements.

4. Terminal Structure (energy dissipater)

When the water flows from the reservoir over the spillway, the static energy is converted into the kinetic energy. This results in very high velocity of flow at the downstream end of the spillway. It may cause serious scour at the downstream end. It may also damage the dam, the spillway and other appurtenant structures. It is, therefore, necessary that the high energy of flow is dissipated before the flow is returned to the river downstream. Terminal structures (or energy dissipaters) are provided at the downstream end of the discharge channel to dissipate the excess energy.

Hydraulic jump basin, a roller bucket, a ski-jump bucket, or some other suitable energy dissipating device is provided for the dissipation of excess energy. Smaller version of such energy dissipaters are also used with check dams and similar small structures.

5. Exit Channel

The exit channels are provided to convey the spillway discharge from the terminal structure to the river downstream. An exit channel is not required for the spillways which discharge water directly into the river downstream.

30.3 Classification of Spillways

The spillways can be classified into different types based on the various criteria, as explained below:

A. Classification Based on Purpose

1. Main (or service) spillway

2. Auxiliary spillway

3. Emergency spillway

B. Classification Based on Control

1. Controlled (or gated) spillway

2. Uncontrolled (or ungated) spillway

C. Classification Based on Prominent Feature

1. Free overfall (or straight drop) spillway

2. Overflow or Ogee spillway

3. Chute (or open channel or trough) spillway

4. Side-channel spillway

5. Shaft (or morning glory) spillway

6. Siphon spillway

30.4 Classification Based on Purpose

a. Main (or service) Spillway

A main (or service) spillway is the spillway designed to pass a prefixed or the design flood. This spillway is necessary for all dams and in most of the dams, it is the only spillway. Therefore, in general terms, the spillway means the main spillway.

b. Auxiliary Spillway

An auxiliary spillway is usually constructed in conjunction with a main spillway. The main spillway is usually designed to pass floods which are likely to occur more frequently. When

the floods exceed the designed capacity of the main spillway, the auxiliary spillway comes into operation and the total flood is passed by both the spillways.

c. Emergency Spillway

An emergency spillway is sometimes provided in addition to the main spillway. It comes into operation only during an emergency which may arise at any time during the life of the dam. Thus an emergency spillway is an additional safety valve of the dam. Some of the conditions which may lead to emergency are as follows:

(i) When the actual flood exceeds the design flood.

(ii) When there is an enforced shutdown of the outlets.

(iii) When there is malfunctioning of spillway gates.

(iv) When there is damage or failure of some part of the main spillway.

(v) When a high flood occurs before the previous flood has been evacuated by the main spillway.

The emergency spillway is generally in the form of a fuse plug or a breaching section which is washed out as soon as the water level in the reservoir reaches a predetermined elevation. The breaching section is sometimes called fuse plug spillway.

(i) An auxiliary spillway is designed to discharge a portion of design flood. An auxiliary spillway operates when the flood is less than the design flood but it is more than the capacity of the main spillway; whereas an emergency spillway operates only when the design flood is exceeded.

(ii) An auxiliary spillway may be of any type, but the emergency spillway is usually a fuse plug.

(iii) An auxiliary spillway may also be designed to work as an emergency spillway when the design flood is exceeded. It works as an auxiliary spillway when the flood exceeds the capacity of the main spillway but it is less than the design flood.

30.5 Classification Based on Control

a. Controlled (or gated) Spillway

A controlled spillway is one which is provided with the gates over the crest to control the outflow from the reservoir. In the controlled spillway, the full reservoir level (F.R.L.) of the reservoir usually coincides with the top level of the gates. Thus the water can be stored up to the top level of the gates. The outflow from the reservoir can be varied by lifting the gates to different elevations. It may be noted that in a controlled spillway the water can be released from the reservoir even when the water level is below the full reservoir level. Depending on the flow release requirement, some selected gates may also be opened.

b. Uncontrolled (or ungated) Spillway

The gates are not provided over the crest to control the outflow from the reservoir. The full reservoir level (F.R.L.) is at the crest level of the spillway. The water escapes automatically when the water level rises above the crest level. Thus the main advantage of an uncontrolled spillway is that it does not require the gates, the operator and lifting power of the operator to operate the gates.

30.6 Classification Based on the Pertinent Feature

There are 8 different types of spillways based on the pertinent feature.

(1) Overfall Spillway

A free overfall spillway (or a straight drop spillway) is the one in which the control structure consists of a low-height, narrow-crested weir and the downstream face is vertical or nearly vertical so that the water falls freely more or less vertical. The overflowing water may discharge as a free nappe, as in the case of a sharp-crested weir, or it may be supported along the narrow section of the crest.

Sometimes, the crest of the spillway is extended in the form of an overhanging lip for directing the discharge away from the downstream face. In all cases, the nappe is properly ventilated to prevent pulsating and fluctuating jets. If the tail water depth is adequate, a hydraulic jump may be formed after the jet falls from the crest, which can be used for the dissipation of energy. However, a long flat apron would be required to contain the hydraulic jump. Moreover, the floor blocks and an end sill may also be required for the establishment of the jump. A free overfall spillway is commonly used for a low arch dam whose downstream face is almost vertical. This type of spillway is also used as a separate structure for low earth dams. The design of a free overfall spillway is similar to that of a vertical drop weir. Fig. 30.2 shows the function of overfall spillway.
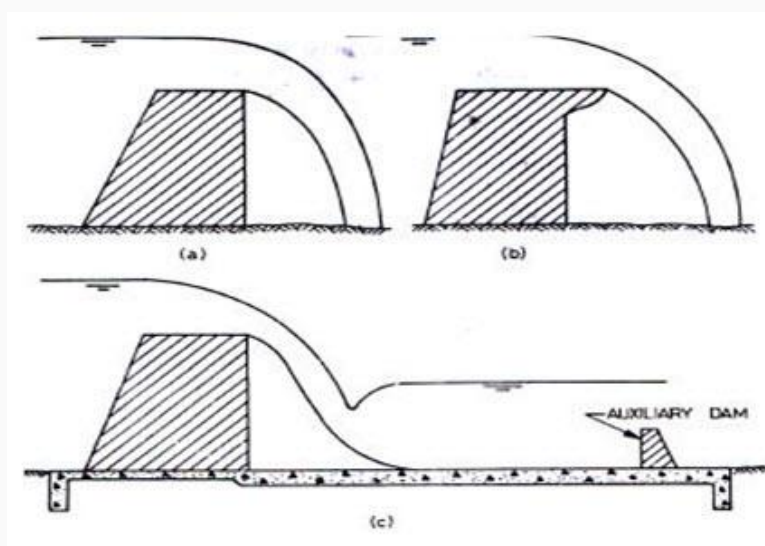

Fig. 30.2. Free overfall spillway.
(Source: http://www.most.gov.mm/techuni/media/CE_05016_ch1.pdf)

(2) Ogee - Shaped (or Overflow) Spillway

An overflow spillway, as presented in fig. 30.3, can be gated or ungated, and it normally provides for flow over a gravity dam section. The flow remains in contact with the spillways surface (except for possible aeration ramps) from the crest of the dam to the vicinity of its base. The ogee or overflow spillway is the most common type of spillway. It has a control weir that is ogee or S-shaped. It is a gravity structure requiring sound foundation and is preferably located in the main river channel, although there are many spillways located on the flanks in excavated channels due to foundation problems.

The structure divides naturally into three zones:

(a) The crest,

(b) The Rear Slope

(c) The Spillway Toe
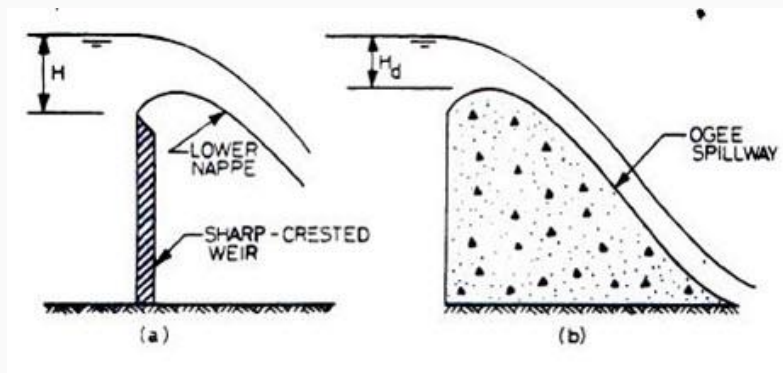
Fig. 30.3. Ogee - Shaped (or Overflow) Spillway.
(Source: http://www.most.gov.mm/techuni/media/CE_05016_ch1.pdf)

3. Chute (or open channel or trough) spillway

A discharge channel downstream of the control structure, known as a chute, as shown in fig. 30.4, may be straight or curved with sides parallel, converging, or diverging. It may be either rectangular or trapezoidal in cross-section and may have either a constant or a variable bottom width. Discharge channel dimensions are governed primarily by hydraulic requirements but the selection of profile, cross-sectional shape, width, and length is influenced by geological and topographical features at the site. Open channels excavated in the abutment usually follow the ground surface profile.

For earth dams and rockfill dams, a separate spillway is generally constructed in a flank or a saddle away from the dam if a suitable site exists. Sometimes, even for a gravity dam, a separate spillway is required when the valley is narrow and an overflow spillway cannot be provided at the dam site. The chute spillway is generally most suitable for such conditions.
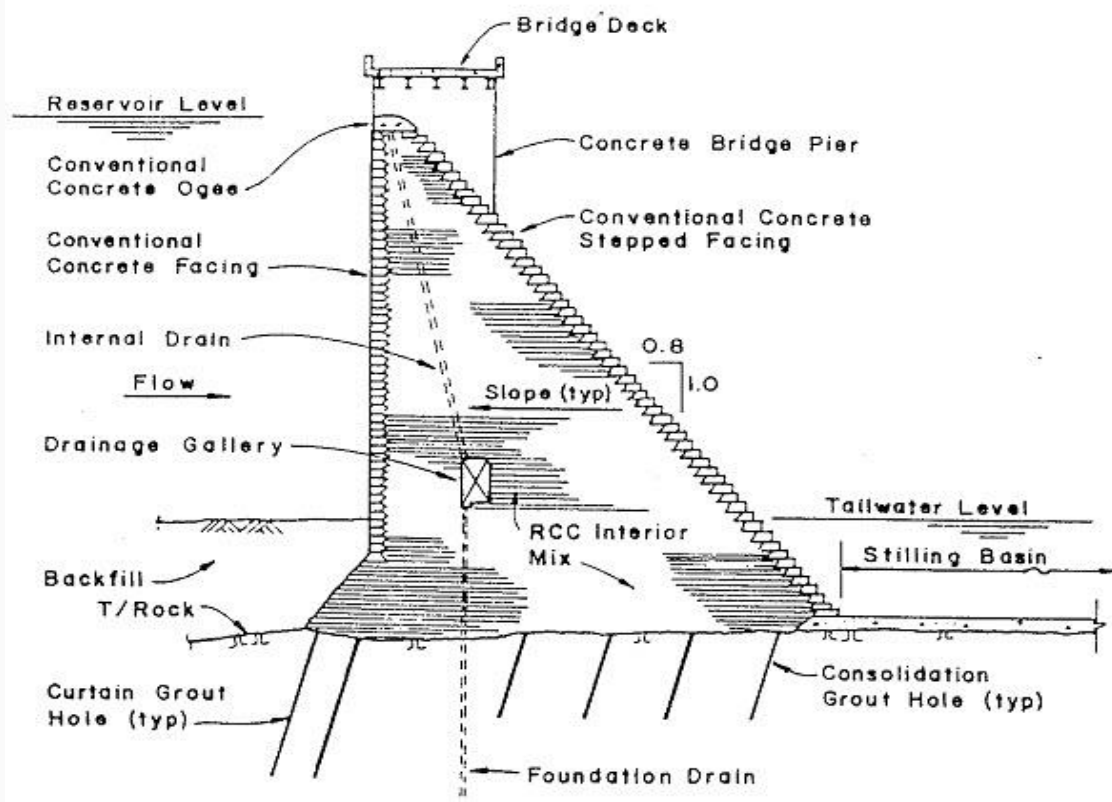
Fig. 30.4. Chute spillway. (Source: http://www.media.rmutt.ac.th/media/e-Book/Engineer/Hydraulic%20and%20Pneumatic/Hydraulic%20Design%20Handbook/0071449590_ar017.pdf)

4. Side-Channel Spillway

A side-channel spillway can be gated or ungated and provides for flow into a chute or tunnel at right angles because the abutment topography is not favorable for a normal crest alignment. A side channel spillway combines an overfall section with a channel parallel to it, which carries the spillway discharge away to a chute or a tunnel. The analysis of flow in a side channel spillway has undergone gradual refinement over the years. The simplest form of analysis is based on the law of conservation of linear momentum, assuming that the only force producing motion in the channel results from the fall of water surface in the direction of spillway axis. The energy of the flow falling down the crest is assumed to be dissipated through it intermingling with the channel flow and offers no assistance in moving the water. Fig. 30.5 shows the arrangement of typical of a side- channel spillway.
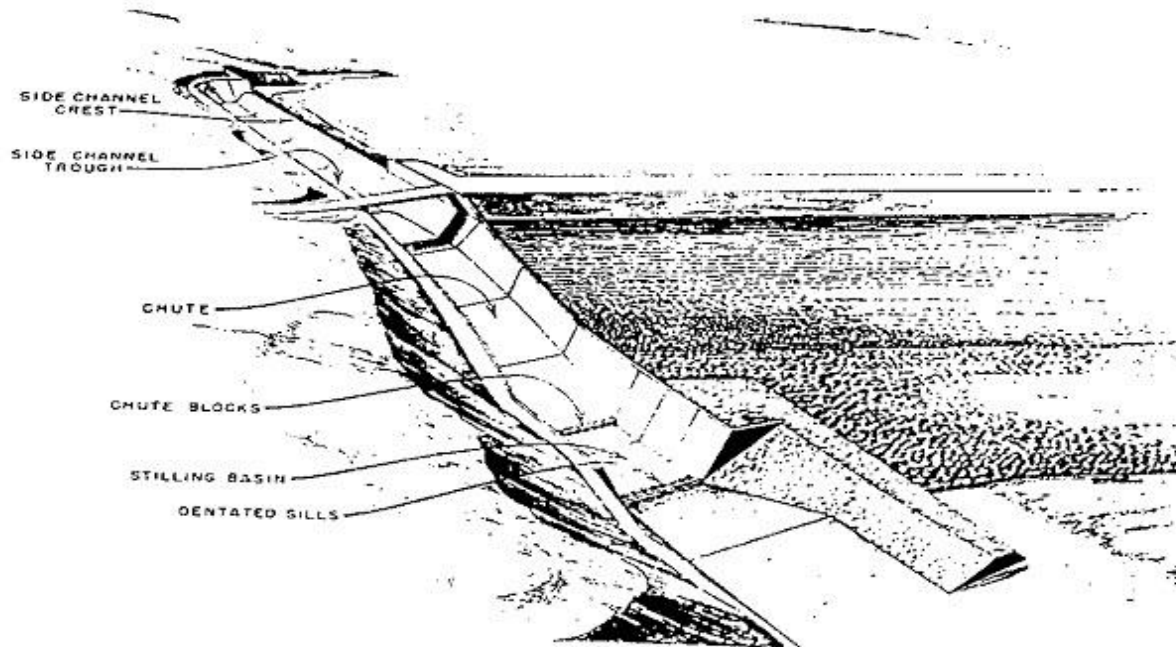
Fig. 30.5. Typical arrangement of a side-channel spillway.
(Source: http://www.media.rmutt.ac.th/media/e-Book/Engineer/Hydraulic%20and%20Pneumatic/Hydraulic%20Design%20Handbook/0071449590_ar017.pdf)

5. Shaft (or Morning Glory) Spillway

A shaft (or morning glory) spillway consists of a large vertical funnel, with its top surface at the crest level of the spillway and its lower end connected to a vertical (or nearly vertical) shaft. The other end of the vertical shaft is connected to a horizontal (or nearly horizontal) conduit or tunnel, which extends through or round the dam and carries the water to the river downstream (Fig. 30.6). When the water level rises above the crest level, it starts overflowing the crest and drops from the rim of the funnel into the vertical shaft and then flows in the horizontal conduit, which conveys it past the dam. The transition between the shaft and the horizontal conduit should be smooth to avoid cavitation. A shaft spillway is used at the sites where the conditions are not favorable for an overflow spillway or a chute spillway. It is generally considered undesirable to construct a spillway just adjacent to an earth dam. Therefore, an overflow spillway is ruled out if there is not an adequate space. If the topography of the site is also such that a chute spillway cannot be constructed, a shaft spillway may be considered as an alternative to a side channel spillway.
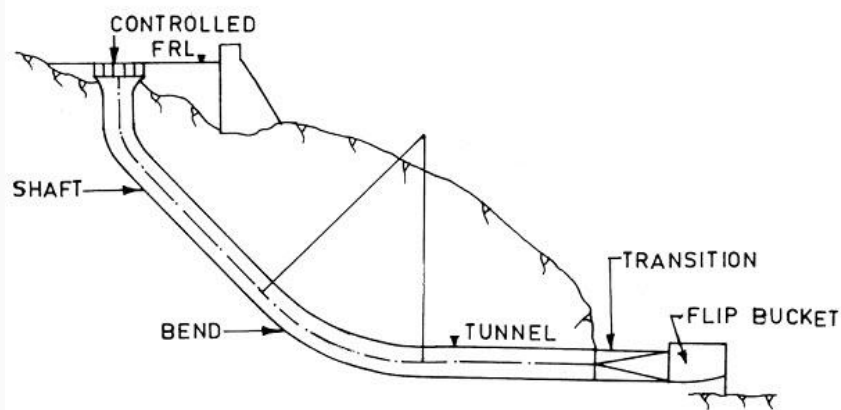
Fig. 30.6. Shaft (or Morning Glory) Spillway. (Source: Khatsuria, R. M., 2005)

6. Siphon Spillway

The discharge over an overflow spillway is a function of the head measured over its crest. Enclosing the crest and making the resulting conduit flow full can substantially increase this effective head. The head on the spillway is then the difference in elevation between the reservoir surface and the spillway outlet. However, the flow near the crest of the spillway would then be under a negative pressure. In other words, the conduit becomes a siphon. All necessary precautions must be taken to ensure that the vacuum is maintained and that it does not become so excessive as to cause cavitation. Typical standard siphon spillway shown in fig. 30.7.
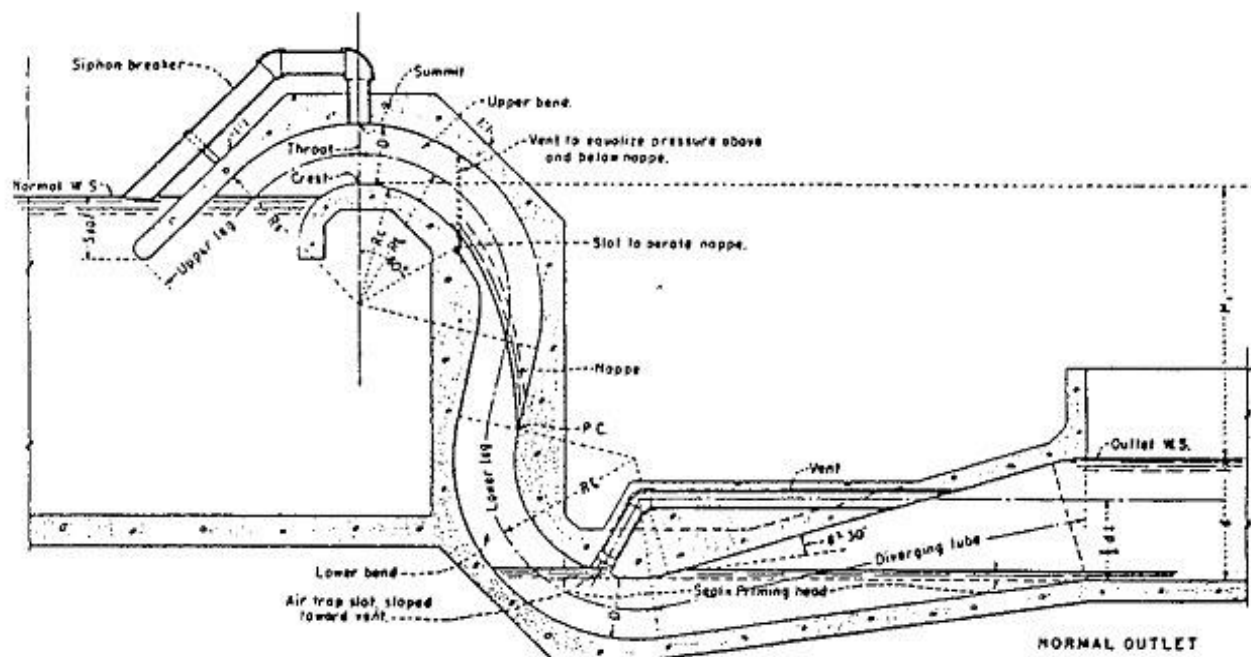

Fig. 30.7. Typical standard siphon spillway. (USBR, 1987).
(Source: http://www.media.rmutt.ac.th/media/e-Book/Engineer/Hydraulic%20and%20Pneumatic/Hydraulic%20Design%20Handbook/0071449590_ar017.pdf)

7. Conduit (or Tunnel) Spillway

Tunnel spillways, as shown in fig. 30.8, are used with embankment dams, where there is no suitable location for a chute spillway. A competent rock abutment is required. Tunnel spillways can be gated or ungated, depending on topographic and geologic constraints at the tunnel entrance. In some cases, gates may be required. A tunnel spillway generally consists of the following elements:

- entrance structure,

- inclined tunnel section,
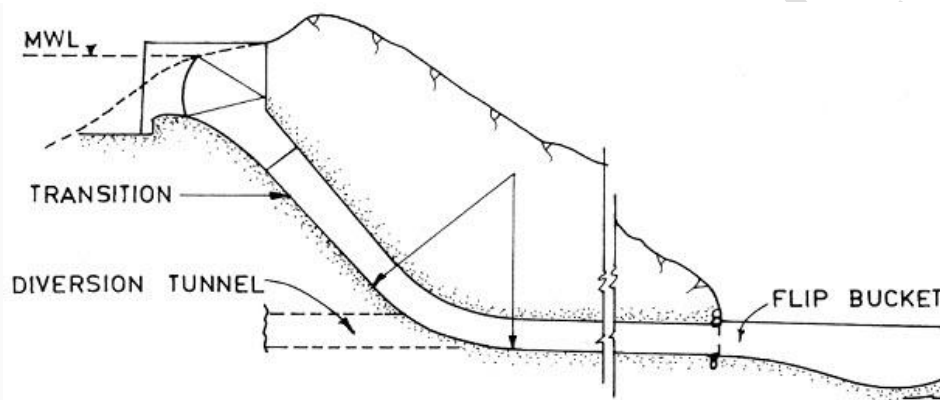
- flat tunnel section, and

- flip-bucket.

Fig. 30.8. Typical Tunnel spillway. (Source: Khatsuria, R. M., 2005)

8. Orifice Spillway

An orifice spillway is normally gated and is used when substantial discharge capacity is needed at low reservoir levels, as illustrated in Fig. 30.10. For instance, it is useful when sediment sluicing is required. It also is useful for diverting flow during construction. Gate sizes are normally smaller for these spillways, but higher head and sealing details can make them expensive. Typical arrangement of an orifice spillway shown in fig. 30.10.
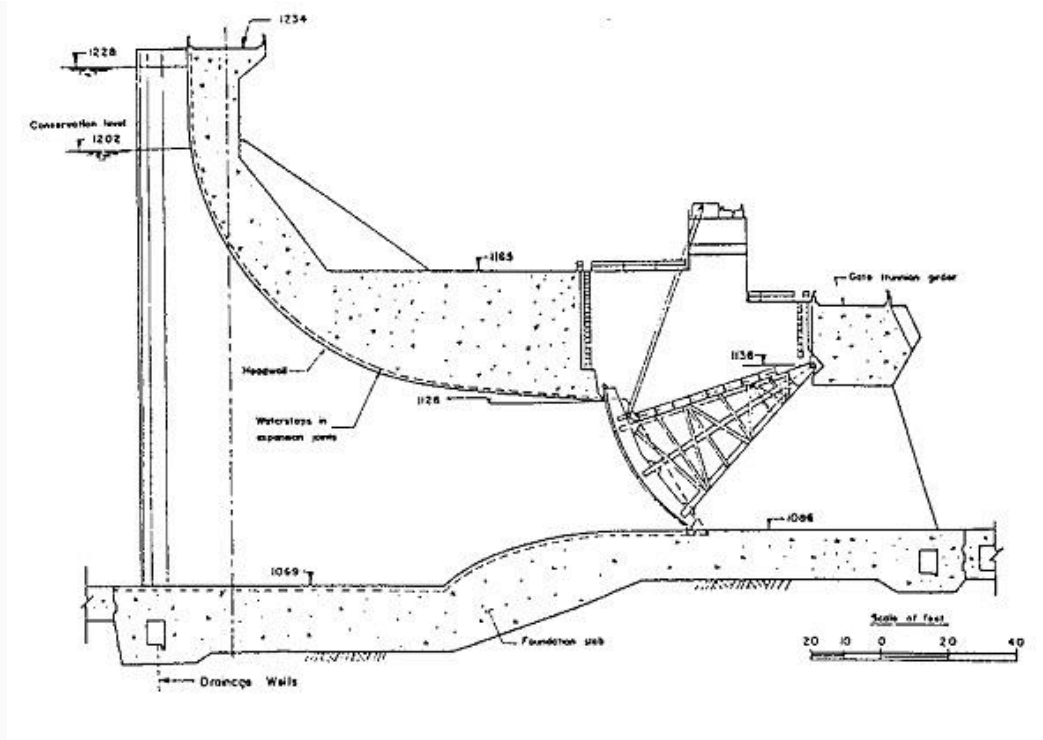
Fig. 30.10. Typical arrangement of an orifice spillway control structure.
(Source: http://www.media.rmutt.ac.th/media/e-
Book/Engineer/Hydraulic%20and%20Pneumatic/Hydraulic%20Design%20Handbook

Lesson 31 Permanent Structures - I

31.1 Concrete Dam

A concrete dam is a structure designed and built for the purpose of holding back water and is constructed across the path of a river or a stream. Dams are built for a variety of reasons, including flood control, power generation, drinking water supply, irrigation, etc. A concrete dam is the strongest type of dam built in modern times and may take several forms. Concrete itself is a building material made from water, cement, sand and gravel, or aggregate. Dams constructed using concrete have three basic designs. An arch dam is a curved, relatively thin curtain of concrete, with the concave side of the curve facing downstream. This type of dam is made of solid concrete that is reinforced with steel. It relies on the pressure of the water behind it to add strength as the components of the resulting force push the sides of the dam into the walls on either side. Arch dams are particularly well suited for areas where a river flows at the bottom of steep canyons or gorges with solid rock at the banks. Some of the important dams in India are Bhakra (Punjab), Idduki (Kerala), Sardar Sarovar (Gujarat), Almaty (Karnataka), etc.

A gravity dam, as shown in fig. 31.1, is a type of dam that relies on its own mass to keep it stable and to hold back water. Gravity dams are often massive structures. The dam is made of concrete, but the main portion of its interior has core fill of rock rather than solid concrete. A gravity dam is usually not curved, and a cross section will resemble a right triangle, with the right angle at the bottom on the side facing the water and the side facing away from the water sloping downward so that the dam is thicker at the bottom. Gravity dams are better for areas where there is no firm bedrock or canyon walls for anchorage.

The third main type of concrete dam is the arch-gravity dam, which combines the features of both the arch dam and the gravity dam. Arch-gravity dams are curved dams that use the principle of the arch to bolster their strength but are much thicker than a typical arch dam and have a core of fill. They are designed so that their massive weight, combined with the increased strength of an arch over a straight line structure, will keep the dam in place and hold back the water.

Fig. 31.1. Bhakra Dam, a concrete dam in the India. (Source: http://www.realtyfact.com/bhakra-dam/)

31.2 Flood Dam

A flood dam, as shown in fig. 31.2, operates as part of a flood control system to protect communities from uncontrolled flood waters. Such dams do not create reservoirs to store water for use in the future, nor do they generate hydroelectric power. They can be installed by government agencies and communities, and are subjected to regulation for safety. A flood dam needs to meet building guidelines and regulators can inspect it periodically to confirm if it is in good working order. In heavy rains, or when runoff from upstream becomes heavier than usual, the flood dam action starts. It retains water and controls its release to slowly allow levels of lakes and rivers to stabilize. In addition to protecting communities from flood waters, this measure also limits topsoil loss and other environmental problems that can occur in severe flooding. When conditions return to normal, the flood control dams can go back into a dormant mode.

Construction of large dams requires certain favourable site characteristics, such as a solid (rock) subbase, strong and stable (rock) sides, narrow section of the river, relatively steeper river gradient, no dominant seismic hazard in the region (however, dams are designed and constructed even in high seismic regions by design modifications), etc. Everywhere such specific site characterics are not found. Hence, the sites for high dam construction are limited. High dams constructed in flatter terrain involve large area inundation that displaces people causing misery to them. Stopping of the natural flow of a river, rehabitation and resettlement issues for the displaced persons, loss of forest land, methane production from the vegetation submerged under the reservoir water, are some of the major environmental issues and concerns in India these days.

Fig. 31.2. Flood Dam (India's hydroelectric projects, such as this dam on the River Teesta). (Source: http://www.nature.com/news/flood-of-protest-hits-indian-dams-1.11932)

31.3 Gabions

Gabion walls are flexible structures where the design is based on the mass of the gabions providing stability against the over turning forces due to the soil and surcharges, as shown in fig. 31.3.
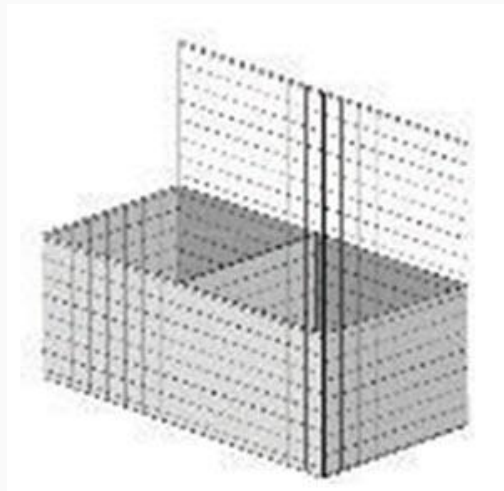
Fig. 31.3. PVC coated Gabions.
(Source: http://www.burdens.co.uk/sites/default/files/literature/ENVIROMESH_BROCHU
RE.pdf)

Types of Gabion Structures

(a) Box-Shaped Gabion

Gabion box-shaped structure is the most popular type of gabions of universal application. This means that if you wish, you can leave all attempts to optimize the design and just use the box-shaped gabions of most appropriate size. They have a classic structure - rectangular wire mesh filled with stones, and can be used for the construction of retaining walls, building mounds and banks, or for landscaping, Fig. 31.4 shows the box shaped gabion.

Fig. 31.4. Box-Shaped Gabion.
(Source: http://www.burdens.co.uk/sites/default/files/literature/ENVIROMESH_BROCHU
RE.pdf)

Gabions box-Large (Jumbo Gabions)

When it comes to fast large-area coverage, we recommend the use of Jumbo - increased gabion structures, which can reach a length to 6 meters. This allows saving time for example,

when installing a retaining wall or terrace, where the decisive importance is the length of the object. Such gabion structures could save you money, at least in the installation.

(b) Reno Mattresses

Reno Mattresses is another type of box gabion structures, which differs from other gabions in length and height. The principle of the device of this type of gabions is that it often has a height of only a few centimeters and is used when one wants to quickly cover a large area and do not lift it, but just strengthen it.

(c) Sack Gabions

Gabion structures in the form are recommended for the erection of towers. Of course, the usual box-shaped gabions are also suitable for this, but you can not lose sight of the design idea for your project: perhaps it is based on rounded objects and the absence of any kind whatsoever angles.

Application

Roadway Protection, Retaining Walls, Rock fall Protection, Bridges and Culverts Protection, Coastline Structure and Protection, Channel Lining. Roadway Protection: The protection of highways and roads from environmental disasters are facilitated with the use of R gabions that stabilize the slopes protecting the shoulders.

Retaining Walls

Gabions used as retaining walls are functional, economical solution and a good alternative to other types of retaining structures due to their flexibility and permeability, as sown in fig. 31.5.

Fig. 31.5. PVC coated woven wire gabions being used as a high retaining wall. (Source: http://www.burdens.co.uk/sites/default/files/literature/ENVIROMESH_BROCHURE.pdf)

Rock Fall Protection

Rolls of fabric with lacing, done by joining together, are provided as a blanket to cover the surface of the slopes to protect any infrastructure built on the foot of the slopes against rock fall. Gabion constructed as retaining wall is an alternative, as illustrated in fig. 31.6.

Gulley and Ravine Control Structures

Fig. 31.6. Rock fall protection netting.
(Source: http://www.burdens.co.uk/sites/default/files/literature/ENVIROMESH_BROCHU RE.pdf)

Bridges and Culverts Protection

Bridge abutments and culverts are potentially at risk of scouring during heavy rains and strong flow of water. Gabion boxes and mattresses can be used as abutments and protective structure that aid the flow of water avoiding the danger of erosion due to their good permeability characteristics.

Coastline Structure and Protection

Gabions and mattresses are highly resistant to corrosion and other environmental effects which are suitable for marine works such as: retaining walls, ramps, beach protection, small jetties, groins, and piers built at great speed and minimum cost. The use of gabions and mattresses dissipate wave energy conserving beaches from being eroded.

Channel Lining

Channels are protected using gabion and mattress structures against erosion which control and guide the movement of water naturally.

Boundary or Security Fences

Units can be used as fences which are cost effective as compared to concrete fences.

31.4 Coffer Dam

It is an enclosure constructed around the construction site to exclude water so that the construction can be done in dry. A coffer dam is thus a temporary dam constructed for facilitating construction. These structures are usually constructed on the upstream of the main dam to divert water into a diversion tunnel (or channel) during the construction of the dam. When the flow in the river during construction of hydraulic structures is not much, the site is usually enclosed by the coffer dam and pumped dry. Sometimes a coffer dam on the downstream of the dam is also required. Fig. 31.7 shows a coffer dam.

Fig. 31.7. Coffer dam at Karcham, Himanchal Pradesh, India.
(Source: http://www.alltravels.com/india/himachal-pradesh/morang/photos/current-photo-80811149)

31.5 Concrete Arch Dam

Concrete arch dams are built in narrow, steep-walled canyons. The canyon walls take up the thrust exerted by the arch and the pressure of the water. Such dams can be extraordinarily thin. Vaiont Dam is 265 meters high, but only 22.7 meters thick at its base. In comparison, Hoover Dam is 221 meters high and 201 meters thick at its base and has a partial arch effect. In India, Idduki dam is known as Concrete arch dam, situated in Kerela (Fig. 31.8).
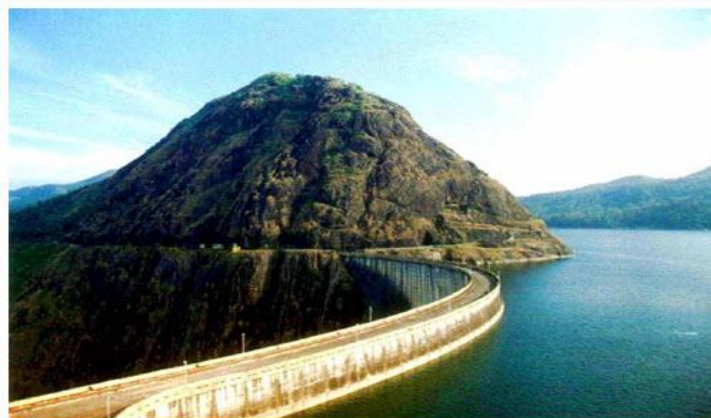
Fig. 31.8. Concrete Arch dam (Idukki dam). (Source: http://tourmet.com/wp-content/uploads/2013/05/215-Idukki-Arch-Dam1-idukki.jpg)

31.6 Buttress Dam

Buttress Dams are made from concrete or masonry. The dam is supported at the downstream face by triangular shaped walls, called buttresses, at a suitable interval. They resist the force of the reservoir water trying to push the dam over. The buttress dam was developed from the idea of the gravity dam, except that it uses a lot less material due to clear spaces between the buttresses. Like gravity dams, they are suited to both narrow and wide valleys, and they must be constructed on sound rock, Fig. 31.9 shows buttress dam in Arizona.

Fig. 31.9. Bartlett Dam in Arizona is an example of a reinforced concrete, multiple arch and buttress dam; it consists of 10 arches, nine buttresses and two gravity wing dams. (Source: http://www.teachengineering.org/view_lesson.php?url=collection/cub_/lessons/cub_dams/cub_dams_lesson02.xml)

31.7 Embankment Dam

Embankment dams are mainly made from natural materials. The two main types are earthfill dams and rockfill dams. Earthfill dams are made up of compacted earth, while rockfill dams are made up mainly from dumped and compacted rockfill. The materials are usually excavated or quarried from nearby sites, preferably within the reservoir basin.

A cross-section (or slice) through an embankment dam shows that it is shaped like a bank, or hill. Most embankment dams have a central section, called the core, made from impermeable material to stop water passing through the dam. Clayey soils, concrete or asphaltic concrete can be used for the core.
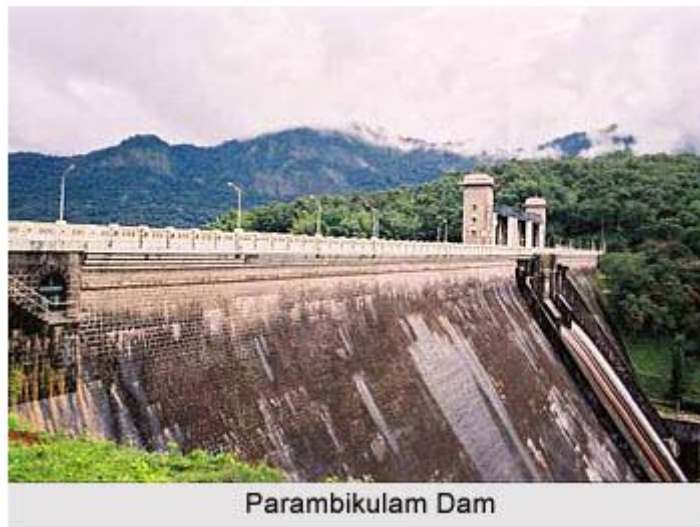
Fig. 31.10. Embankment dam (Parambikulam dam, India).
(Source: http://www.indianetzone.com/33/parambikulam_dam_kerala.htm)

Lesson 32 Permanent Structures - II

32.1Rubble Masonry Dam

These dams are used in gullies or stream channels with high rates of runoff or where vegetation cannot be established. The construction of this dam is recommended only, where rocks or stones are readily available in nearby areas. The minimum thickness of walls is kept as 30 cm. The downstream slope below the spillway is kept at least 1:2. The thickness of the base should not be less than 3/4th of the height of the dam. As shown in fig. 32.1.

Some details of rubble masonry dams are given as under:

- The minimum thickness of side walls cut off walls and apron should be about 30 cm.

- The thickness of main wall from the crest of spillway to the top of dam should not be less than 35 cm.

- To ensure proper settling, the upstream side of dam should be maintained at an angle of about 10° with the vertical.

- The length of apron should not be less than 1.5 times the height of dam, measured from apron floor to the spillway's crest.

- For drainage, the provision of drains or weep holes should also be made. They should be located near the base of dam.

Fig. 31.1. Rubble-masonry gravity arch dam.
(Source: http://www.nps.gov/nhl/DOE_dedesignations/Roosevelt.htm)

32.2 Sand Detention Dam

The basic purpose of silt detention dam, as shown in fig. 32.2, is to detain the silt load coming along the runoff from the catchment area into depressed part and simultaneously to harvest water. The location of such dam is decided at the lower reaches of the catchment where water enters the valley and finally made for taking out the water for irrigation purpose. For better result, a series of such dams can be constructed along the slope of catchment.


Fig. 31.7. Sand Detention Dam (Smoky canyon dam)
(Source: http://www.delhur.com/projectTypes/waterResources.html)

33.3 Rubber Dam

A symbol of sophistication, simple and efficient design, this most recent type of dam uses huge cylindrical shells made of special synthetic rubber and inflated by either compressed air or pressurized water. Rubber dams offer ease of construction, operation and commissioning in tight schedules. These can be deflated when pressure is released and hence, even the crest level can be controlled to some extent. Surplus waters would simply overflow the inflated shell. They need extreme care in design and erection and are limited to small projects. Example of Rubber type: Janjhavathi Rubber Dam (India) as illustrated in fig. 32.3.
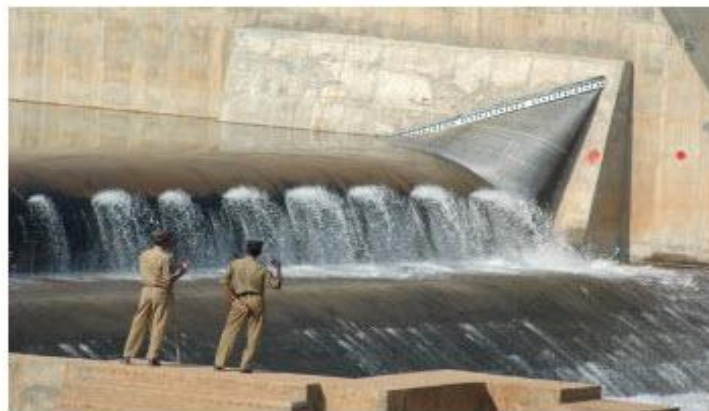
Fig. 31.10. Janjhavathi Rubber Dam (India).
(Source: http://www.thehinduimages.com/hindu/photoDetail.do?photoId=6452707)

32.4 Steel Dam

A steel dam, as illustrated in fig. 32.4, consists of a steel framework, with a steel skin plate on its upstream face. Steel dams are generally of two types: (i) Direct-strutted, and (ii) Cantilever type. In direct strutted steel dams, the water pressure is transmitted directly to the foundation through inclined struts. In a cantilever type steel dam, there is a bend supporting the upper part of the deck, which is formed into a cantilever truss. This arrangement introduces a tensile force in the deck girder which can be taken care of by anchoring it into the foundation at the upstream toe. Hovey suggested that tension at the upstream toe may be reduced by flattening the slopes of the lower struts in the bent. However, it would require heavier sections for struts. Another alternative to reduce tension is to frame together the entire bent rigidly so that the moment due to the weight of the water on the lower part of the deck is utilized to offset the moment induced in the cantilever. This arrangement would, however, require bracing and this will increase the cost. These are quite costly and are subjected to corrosion. These dams are almost obsolete. Steel dams are sometimes used as temporary coffer dams during the construction of the permanent one. Steel coffer dams are supplemented with timber or earthfill on the inner side to make them water tight. The area between the coffer dams is dewatered so that the construction may be done in dry for the permanent dam. Examples of Steel Dam: Redridge Steel Dam (USA) and Ashfork-Bainbridge Steel Dam (USA).

Fig. 31.12. Redridge Steel Dam.
(Source:http://commons.wikimedia.org/wiki/File:Redridge_Steel_Dam_UpstreamSide_GateControls_DSCN2191.JPG)

32.5 Diversion Dam

A diversion dam is constructed for the purpose of diverting water of the river into an off-taking canal (or a conduit), as shown in Fig. 32.5, which represent Indian dam. They provide sufficient pressure for pushing water into ditches, canals, or other conveyance systems. Such shorter dams are used for irrigation, and for diversion from a stream to a distant storage reservoir. It is usually of low height and has a small storage reservoir on its upstream. The diversion dam is a sort of storage weir which also diverts water and has a small storage. Sometimes, the terms weirs and diversion dams are used synonymously.

Fig. 31.12. Picture of Koyna Dam in Satara district, Maharashtra.
(Source: http://www.thehindu.com/news/national/other-states/irrigation-water-diverted-for-industries-and-domestic-use-in-maharashtra/article4609969.ece)

32.6 Storage Dam

They are constructed to store water during the rainy season when there is a large flow in the river. Many small dams impound the spring runoff for later use in dry summers. Storage dams may also provide water supply, or improved habitat for fish and wildlife. They may store water for hydroelectric power generation, irrigation or for a flood control project. Storage dams are the most common type of dams and in general the dam means a storage dam unless qualified otherwise. One of example shown in fig. 32.6 which is one of the tallest dam in the world.

Fig. 31.13. Tehri dam of India. (Source: http://www.indiamike.com/india-images/pictures/tehri-dam)

32.7 Timber Dam

Main load-carrying structural elements of timber dam are made of wood, primarily coniferous varieties such as pine and fir. Timber dams,as presented in fig. 32.7, are made for small heads (2-4 m or, rarely, 4-8 m) and usually have sluices; according to the design of the apron they are divided into pile, crib, pile-crib, and buttressed dams. The openings of timber dams are restricted by abutments. When the sluice is very long, it is divided into several openings by intermediate supports: piers, buttresses, and posts. The openings are covered by wooden shields, usually several in a row one above the other. Simple hoists—permanent or mobile winches—are used to raise and lower the shields.

Fig. 31.11. Timber Dam.
(Source: http://blog.thecivilengg.com/wpcontent/uploads/2011/09/timber-dam.jpg)

32.8 Earth Dam

An earth dam is made of earth (or soil) built up by compacting successive layers of earth, using the most impervious materials to form a core and placing more permeable substances on the upstream and downstream sides. A facing of crushed stone prevents erosion by wind or rain, and an ample spillway, usually of concrete, protects against catastrophic washout should the water overtop the dam. Earth dam resists the forces exerted upon it mainly due to shear strength of the soil. Although the weight of the structure also helps in resisting the forces, the structural behavior of an earth dam is entirely different from that of a gravity dam. The earth dams are usually built in wide valleys having flat slopes at flanks (abutments).The foundation requirements are less stringent than those of gravity dams, and hence they can be built at the sites where the foundations are less strong. They can be built on all types of foundations. However, the height of the dam will depend upon the strength of the foundation material.

Examples of earthfill dam: The Banasura Sagar dam, which is the largest earthen dam in India and the second largest in Asia, impounds the waters of the Karamanathodu, a tributary of the Kabini river.

Gulley and Ravine Control Structures

Fig. 32.4. The Banasura Sagar dam. (Source: http://www.banasura.com/banasura-sagar-dam)

32.9 Institutions/Organizations dealing with Soil Conservation Related Issues in India

32.9.1 Central Arid Zone Research Institute, Jodhpur, Rajsthan

India has about 14 per cent of its area under arid climate, 10 percent under hot arid, mostly in Rajasthan and Gujarat states, and 4 percent under cold arid, largely in Jammu and Kashmir state. Because of its harsh environment, agriculture in arid zones is a formidable challenge. Central Arid Zone Research Institute, Jodhpur, a Premier Organization of the Indian Council of Agricultural Research (ICAR), is an autonomous organization under the Department of Agricultural Research and Education, Ministry of Agriculture, Government of India The CAZRI operates through Six Divisions, located at the headquarters in Jodhpur. There are four Regional Research Stations located in different agro-climatic zones to work on location-specific problems. (http://www.cazri.res.in/)

32.9.2 Hazaribagh, Jharkhand

The Soil Conservation Department of Damodar Valley Corporation (DVC), one of the prime river valley projects in the country has been engaged in the task of promoting soil conservation and afforestation in the catchment of the Damodar-Barakar river system for more than five decades now. Four major dams namely, Tilaya, Konar, Maithan and Panchet were constructed between the years 1953 and 1959 with the corresponding catchment areas of 984, 997, 6293 and 10966 km². The effective reservoir lives of these four dams were estimated as 151, 219, 245 and 97 years, respectively, based on silt observation in the rivers near the dam location. A reservoir sedimentation survey was conducted at Maithon and Panchet, respectively in 1963 and 1962, and the reservoir lives were revised downwards to 98 years and 38 years, respectively due to excessive soil erosion from the catchment areas. The initial soil conservation measures were generally ineffective because the anthropogenic factor was

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overlooked. The DVC carried out with mainly engineering measures for runoff conservation and sediment control; deforestation of the catchment, overgrazing, unscientific cultivation in the catchment areas continued unabated. Besides, there was a lack of maintenance of the constructed structures. Alerted by the huge reduction in the estimated reservoir lives at Maithon and Panchet, integrated conservation effort was initiated from the mid nineteen sixties and the local community was also involved in this effort. As a result, the reservoir sedimentation survey conducted again in the year 1987 for Maithon and in 1985 for Panchet revealed an estimated increase in the reservoirs to 138 years and 108 years, respectively (Adapted from DVC 1999).

32.9.3 Central Water Commission, Govt. of India

Central Water Commission is a premier Technical Organization of India in the field of Water Resources and is presently functioning as an attached office of the Ministry of Water Resources, Government of India. The Commission is entrusted with the general responsibilities of initiating, coordinating and furthering in consultation of the State Governments concerned, schemes for control, conservation and utilization of water resources throughout the country, for purpose of Flood Control, Irrigation, Navigation, Drinking Water Supply and Water Power Development. It also undertakes the investigations, construction and execution of any such schemes as required. (http://www.cwc.nic.in/)

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