IRRIGATION ENGINEERING

CHAPTER I

DEFINITIONS AND GENERAL

1. Introductory: In this chapter, will be given a few definitions and a few articles of general interest. It is absolutely necessary to know these in order to appreciate better the other chapters that follow. At this stage, readers are advised to read chapter XXVII on Metric system before studying any more articles of chapter I.

2. Definitions: Irrigation is defined as the artificial application of water on an agricultural land for the assured growth of plant life. Hence, if a crop is raised on rain water falling directly on a land on which the crop stands, we say that the crop has not been irrigated. Such a crop is called a rain-grown crop. If, on the other hand, water from its source of supply is guided to the land and is applied on it to raise a crop, that crop is said to have been irrigated. Such water as is applied artificially is called irrigation water and such a crop is called irrigated crop. The application of irrigation water involves some effort on the part of man. Rain water falling directly on a land does not involve such effort on the part of man and it is therefore not called irrigation water. An irrigation engineer is one who helps to bring irrigation water from its source of supply to an agricultural land. Irrigation Engineering is a science that tells us about the ways and means adopted by the irrigation engineer to achieve this object. It describes to us quite an interesting story about the struggle of irrigation engineer with that intractable element called water. It tells us, to what extent the land and water have been utilized for the growth of plant life and, with what successes and failures. The whole story is indeed fascinating for it is so common, so natural and of much vital importance. An irrigation engineer has to construct certain masonry and concrete works to realize his dreams. These works are called irrigation works.
3. Brief review of the development of irrigation practice and technique in India: As already said in prelude, irrigation engineering started with the musing man of forest, who loved Nature and its forces and who gradually tamed these forces for his own convenience. The culture of India is founded on the bed-rock of Vedas and is essentially the culture of forest. That is probably one of the reasons why India leads practically the whole world in the field of irrigation engineering. The total irrigated area in India, this day, is of the order of 79 million acres (about $32 \times 10^6$ hectares) out of the total annually cultivated area of about 385 million acres (about $156 \times 10^6$ ha). Culturable or cultivable area is 480 million acres (about $194 \times 10^6$ ha). About 286 million acres are under food crops and about $\frac{1}{5}$th of this area is irrigated.

In Rig Veda, Yajur Veda and Atharva Veda, mention is made about irrigation works in some chapters. But in the last mentioned Veda, the beauty and excellence of ancient man is simply striking when he says, "As a cow is to calf, so is a river to main canal".

Among epics, the Mahabharata mentions tanks and the Ramayana has made a reference to the training of river Ganga by King Bhagirath.

So far as the Puranas are concerned, mention about canals and wells is made in the Devi Purana and the Vishnu Purana.

Smritis say abundantly about irrigation and irrigation works. Special mention may be made of Manu Smriti and Brahaspati Smriti. There-in, the construction of irrigation works is characterized as one of the righteous actions and, king and rich persons of a country are enjoined to consider it as their sole duty and responsibility to help poor by providing irrigation facilities to them.

Sutras are also not silent on the subject of irrigation. Kaushika Sutra tells us about manner in which the opening ceremony of irrigation works was performed in those days by pundits well versed in all the Vedas.
Ancient Hindu rulers followed strictly the injunctions laid down in the Smritis and took a lot of interest in the construction and maintenance of irrigation works. Chandra-gupta Maurya and his prime minister Chanakya are well known. The latter wrote a book by title 'Artha Shastra' in which he has talked about the subject of irrigation at length. Chola rulers of South India evinced enough keenness and zeal to keep their subjects prosperous and happy by constructing the necessary irrigation works.

Amongst the Muslim rulers, Sultan Firoz Tughlaq constructed a number of canals from Sutlej and Jumna rivers in the 14th century. Firozshah canal had been abandoned and Akbar put it again into use in the 16th century. During the reign of emperor Shah Jahan, Hissar canal was remodelled and some other new canals were constructed. The kind-heartedness and love of Shah Jahan are proverbial. This noble ruler took considerable pains to see the cultivators of his empire well off. It was Shah Jahan who, by constructing Taj Mahal, made immortal one tear drop of love! Such was his large-heartedness.

In 19th century, during the British period, three important irrigation works were remodelled and opened. They were, Western Jumna canal, Eastern Jumna canal and Cauvery delta system. These works were gradually followed by many other works like Upper Bari Doab canal, Ganga canal and Godavari delta system.

The report of Indian Irrigation Commission of 1901-03, gave a good impetus to the construction of various kinds of irrigation works in India. At present, in India, we have got some of the magnificent irrigation works of world, in the form of solid diversion weirs, barrages, dams, canals and canal masonry works of all types. Thanks to the musing man of forest and the rishis in the field of irrigation engineering who followed him.

This day, in India, there are two statutory bodies at centre known as Central Board of Irrigation and Power and, Central Water and Power Commission with their head quarters at New Delhi. These two bodies look after the development of irrigation, power, flood control, etc. in India and
also advise and help the State Governments when necessary. There is also one irrigation research station in practically each State to solve the problems connected with irrigation and allied subjects. The work of these research stations is co-ordinated by the Central Board of Irrigation and Power.

Since independence in 1947, the Government of India and all the State Governments have constructed many major and minor irrigation projects to increase the food production. Projects here, projects there and projects everywhere! Some of these projects are under construction and some are under investigation and design. Infact, the only solution to tide over the food shortage in an agricultural country like India is that all concerned should be more irrigation-minded. In India, irrigation engineer has indeed a most important role to play in bringing abundantly the happiness to man in the street.

Planning Commission, in the First Five Year Plan (1951-56) which in its final form was presented to Parliament on the 8th December 1952, had rightly emphasized the importance of irrigation projects and had given them the top-most priority. The amount proposed to be spent on irrigation projects was greater than that proposed for any other item in that Five Year Plan. Total outlay of the plan was 1960 crores of rupees, 30% of which was used for development of irrigation and power. About 433 crores were used for irrigation and about 50 crores were used for power. The Second Five Year Plan (1956-61) was outlined and in it too, the development of irrigation was given its well deserved importance. Total outlay of this plan was 4600 crores of rupees, 19% of which was used for development of irrigation and power. About 430 crores were used for irrigation and about 450 crores were used for power. According to the Second Five Year Plan, the total irrigated area was proposed to be stepped up to 88-8 million acres (about $36 \times 10^6$ ha) by 1961. Actually by 1961, the net irrigated area was about 71 million acres ($28 \times 10^6$ ha). The Third Five Year Plan (1961-66) provided 650 crores of rupees for major and medium irrigation only, excluding the allocation for minor irrigation. In this plan the provision for power was 1020 crores of rupees. Thus,
in this plan 1670 crores of rupees were used for irrigation and power and this forms about 22% of the total outlay of 7500 crores of rupees on the Third Five Year Plan. The net irrigated area was proposed to be stepped upto 90 million acres \((37 \times 10^8 \text{ ha})\) by 1966. The actual achievement by 1966 is, however, about 79 million acres (i.e. 32 million hectares). In the draft outline of the Fourth Five Year Plan (1966-71), the outlay proposed for irrigation and flood control is about Rs. 940 crores (post-devaluation rate) of rupees so as to increase irrigated area by 13 million acres. This speaks abundantly of the importance of irrigation engineering to an agricultural country like India and of the keen interest that the Central and State Governments have been taking in the development of irrigation engineering in India. The future holds a great promise in the field of irrigation development and there cannot be the slightest ray of doubt that India will continue to maintain its high traditions in irrigation engineering.

It is indeed significant that India sponsored the establishment of International Committee on Irrigation and Drainage at a meeting held in Simla in June 1950 and India became host country for the First International Congress on Irrigation and Drainage held in Delhi in January 1951.

4. Necessity of irrigation: A crop requires certain quantity of water after certain fixed interval throughout its period of growth. If rain water, falling directly on land on which the crop stands, can satisfy both these requirements, irrigation water will not be required for raising this crop. Thus, in England, the rain as it falls naturally, satisfies both these requirements for practically all crops and therefore, irrigation is not significantly practised in England. Irrigation is, however, necessary in tropical and sub-tropical countries when rain water falling directly on land is either insufficient for the growth of crops or the rain does not fall after fixed intervals as required by the crops. Further, as the amount and frequency of rainfall varies from part to part of a tropical country, certain crop may be irrigated in one part of the country but may not require irrigation water in another part of the same country. It is, interalia, due to this fact that the major irrigation works are in the States of
Sind (now in West Pakistan), Punjab, Uttar Pradesh and Madras. *It is thus out of sheer necessity that the importance of irrigation is greatest in India.* Area where agriculture is not possible without irrigation is called *arid* region. Area in which only inferior crops can be grown without irrigation is called *semi-arid* region.

5. **Land:** India is a subcontinent with varied topography and therefore, the types of irrigation works that are feasible, vary from place to place according to change in the nature of country. The surface soil, ground slope and substrata vary from place to place, thus presenting different problems in different areas in India. The features of land in an area have, to a greater measure, affected the development of irrigation in that area.

6. **Water:** Irrigation water can be taken directly from river. Also, the flow of river in certain locality can be stored in a storage reservoir and the irrigation water can be taken from this reservoir as and when required. Rivers may be snow-fed and rain-fed as in North India or, only rain-fed as in South India. Rivers in North India are *perennial* i.e. the water in *sufficient* quantity flows in them throughout the year. Rivers of peninsular India have a good flow in monsoon season only and many of them are either dry or have negligible flow during most of the remaining part of year.

As rain falls on ground, some of it percolates through the porous surface soil and remains underground. This water below the ground is called *subsoil water.* It can be used for irrigation purposes by lifting it to the surface. Fig. 1 shows some important rivers of India.

7. **Advantages of irrigation:** Following are some of the main advantages or benefits of irrigation:

(a) Government spends a lot of money on the construction of irrigation works and makes irrigation water available to cultivator. It, therefore, charges something for this facility provided to the cultivator. Thus, irrigation works are a paying concern to the Government.
(b) Irrigation helps general development of the country in which it is practised. It assures the proper and successful growth of crops because of regular supply of water according to the requirements of the crops. It also makes possible the growing of those crops that cannot be raised only on rain water falling directly on land. Because of the assured supply of water, two crops can generally be grown in a year and, in some places, even three crops are possible in a year. Irrigation promises self-sufficiency in food which is the basic need of man to keep his body and soul together. In short, irrigation converts an unproductive land into a productive one.

(c) Irrigation protects people from the occurrence of famines when rainfall in any year is severely deficient. Also, the famine-haunted people can be employed on the construction of some irrigation works and this will be a sort of relief to them in their moments of privation and acute distress.

(d) The owner of agricultural land is a gainer as the value of his land will increase if it is served by a near-by canal system.

(e) Hydro-electric power can be generated from falls on some canals or, by the water stored in a storage reservoir. This cheap power will serve many agricultural, domestic and industrial purposes.

(f) Some large canals can serve the dual purpose of irrigation and inland navigation.

8. Possible disadvantages of irrigation: Misuse of anything has ill-effects in store; so has the improper use of irrigation water. When irrigation water is used in excess of the requirements of crops or, when it is applied on a land on which it should not be applied, the land in question becomes alkaline (i.e. salt-affected) and waterlogged and, thus becomes infertile or barren. Such a damaged land can however be reclaimed and made again fertile by adopting proper measures which of course entail extra expenditure of money. Also, when irrigation water is allowed to remain in form of dead pools on the surface of ground, these pools will breed mosquitoes which will cause malaria in the round-
about area. By adopting proper methods, however, this malaria can be controlled.

9. **Types of irrigation**: Following are the main types (i.e. forms or classes or schemes) of irrigation:

   (a) Direct irrigation or River-canal irrigation
   (b) Storage irrigation or Valley irrigation
   (c) Subsoil water irrigation.

   In direct irrigation, water is taken directly from river by means of main canal. To have proper control over the level of water in river, an irrigation work in the form of a solid diversion weir, bandhara, or barrage is constructed across the river. The irrigation works across river or stream are called **head works**. If the water from such head works is available throughout the period of growth of crops irrigated by it, we say that **perennial irrigation** is in vogue from that irrigation scheme. In case of perennial river, water in a canal may be available throughout the year and in such case the canal is known as a **perennial canal**. In case of non-perennial stream, water in a canal may be available for certain period in a year depending on the availability of supply from the source; in such case, the canal is called a **seasonal canal** or non-perennial canal. Inundation irrigation can be called river-canal irrigation: but in this type of irrigation, there is no irrigation work across river to control the level of water in the river. Inundation canal is a seasonal canal as the water is available in it for a particular season in a year. The direct irrigation is usually practised in deltaic tract i.e. in country having even and plain topography. It is feasible when the normal flow of river or stream, throughout the period of growth of crops irrigated, is never less than the requirements of the irrigated crops at any time of this period. The three **phases** of this type of irrigation are:

   (i) Diversion of water from river
   (ii) Conveyance of water to land
   (iii) Application of water on land.

   In case of storage irrigation, the water of a river flowing during rainy season is stored in storage reservoir or tank
formed at the back of a dam constructed across river or stream. This stored water is then used for irrigation, as and when required. This type is feasible when the flow of a river or stream is in excess of the requirements of irrigated crops during a certain part of the year but falls below requirements or is not available at all in the river during remaining part of year. It is usually practised in non-deltaic area i.e. in a country having uneven topography. The canals here are either perennial or seasonal. The three phases of this type of irrigation are:

(i) Storage of river water
(ii) Conveyance of water to land
(iii) Application of water on land.

In the above two types of irrigation, diversion weir or storage dam has other ancillary works also. Further, in each type, necessary canal system is constructed to carry water from river or storage reservoir to the agricultural land that is to be irrigated.

In subsoil water irrigation, usually, open (i.e. percolation) wells and tube wells are constructed to utilize the sub-surface water. The subsoil water is lifted from these wells by some devices and is applied on the land on or near which they are situated. Well irrigation is more widely spread in deltaic areas but it is also practised in non-deltaic tracts. The two phases of this type of irrigation are:

(i) Lifting of water from wells
(ii) Application of water on land.

From some artesian wells, water under pressure is available above the ground but in India such wells are not of much use from irrigation point of view. In certain locations, an inclined underground tunnel called *Karez* is constructed to tap the underground springs and the water so tapped is used for irrigation purposes.

**10. Scope of Irrigation Engineering:** Irrigation engineering deals with all the above-mentioned types of irrigation with respect to all the phases of irrigation, viz.,
(i) Storage, diversion or lifting of water
(ii) Conveyance of water to irrigated land
(iii) Application of water on irrigated land.

It describes the methods of taming and controlling mighty rivers, conserving the water of streams, diverting water into main canals and carrying it to land by means of a net-work of other canals and the necessary canal masonry works. It deals with design, construction and maintenance of all irrigation works.

But that is not enough. Irrigation engineering treats also the agricultural soils, soil moisteres, methods of application of water on land, irrigation water assessment, water-logging, salt efflorescence and the drainage works to reclaim a damaged agricultural land.

Soil erosion seriously affects the fertility of agricultural land and hence, the study of ‘soil erosion and soil conservation’ also forms an important part of irrigation engineering.

On analysing the scope, we find that the study of irrigation engineering has, broadly speaking, two aspects viz.,

(i) The engineering aspect.
(ii) The agricultural aspect.

It will not be out of place to mention here that the present day multipurpose river valley schemes cater for irrigation, water power, flood control, soil conservation, inland navigation, fish culture, malaria control, etc. Therefore an irrigation engineer should have also some working idea about water power, flood control, inland navigation, etc. Hence water power, flood control, inland navigation, etc. are treated in this treatise.

11. Some terms: When irrigation water in canals is available at such a level that it can flow over the adjoining land by gravity, it is a case of flow irrigation. Examples of flow irrigation are the water supplies obtained from practically all canals in the first two types of irrigation; flow irrigation is also practised from fully artesian wells. However, when the water has to be lifted up before it could be applied
on land by gravity, it is a case of lift irrigation. Well irrigation is an example of lift irrigation. In some cases, lift irrigation may have to be practised on some canals having land on both sides at a level higher than the level of water in the canals. In other cases, water is also lifted directly from non-perennial rivers to irrigate land near the banks of these rivers. Flow irrigation is less costly to an irrigator but usually he makes lavish use of such water, creating new problems for solution. Because of the convenience offered by flow irrigation, as far as practicable, the irrigation works are so designed as to effect flow irrigation.

In delta portion of a long river, the river runs on a ridge. Water during floods may overflow the river banks and may flood the bordering land. This flood water is subsequently drained off and crops are grown on the soil saturated with flood water. This is called natural flood irrigation or natural inundation irrigation. During high floods, the water can also be diverted artificially on this bordering high land which is above the normal level of water in the river. Flood water of a few streams in areas of scanty rainfall is utilized in this manner in India, Egypt and elsewhere. In some cases, the subsequent waterings, if required by the crops, are given from open wells dug on the cultivated area of bordering land.

12. Alluvial and non-alluvial soils: Alluvial soils are those soils which have been formed by the agency of water in course of time. In deltaic region, a river carries heavy charge of silt and, when it overflows its banks in flood season, it drops its fine silt-load on the bordering land. This process, continued over long period, forms a soil known as alluvial soil. The area of alluvial soil has very flat surface slope i.e., it is comparatively a plain and even area. Also, in such area, the hard foundation bed is generally not available for placing the structural foundation of irrigation structures upon it. The rivers flowing through such area are comparatively shallow and have a tendency to shift their courses. The river bed consists of sand layer of very great thickness and is permeable. Canals passing through such area are
called *alluvial canals*. Alluvial soil is available in Indo-Gangetic plain and in deltas of big rivers. All the three types of irrigation are possible in this soil, the first type is however most developed and second type is the least in existence there.

*Non-alluvial soil* is the result of disintegration of rock, carried over a very long time. The area of non-alluvial soil has usually an uneven topography and the hard foundation bed for irrigation structures is usually available in this area. The river bed itself consists of hard material and, in some cases, the outcrop of rock may be available at river bed level. The rivers passing through this area have therefore no tendency to shift their courses. Canals passing through this area are called *non-alluvial canals*. The major portion of Maharashtra State is an area of non-alluvial soils. All the three types of irrigation are possible in this area, the second type being most developed and first type being the least in existence. This soil may be impermeable or permeable, though usually impermeable.

13. **Scope of irrigation schemes**: In every irrigation scheme, connected with river flow, the main function of an irrigation engineer is to divert water from the source into main canal either directly or after storing in a storage reservoir. The water so diverted will be conveyed to land and then it will be applied on the land. In the following pages, the likely scope of each type of irrigation scheme is shown. It is however probable that there may not be all the items mentioned because the items actually provided in an irrigation scheme depend on the actual necessity and requirements.

14. **Direct irrigation scheme**: (see fig. 2): The following are the likely items in this scheme:

(i) Head works  
(ii) Distribution works  
(iii) Agricultural land drainage works.

The head works consist of a low diversion weir across river and hence, they are known as *diversion head works*. The
diversion weir may be a *solid weir* with or without crest shutters or, it may be an open weir i.e., a low weir fitted with gates. The latter weir is also called a *barrage* or river regulator. The weir will have *undersluices* or *weir scouring sluices* at one or both of its flanks according as the main canals on one or both sides take off from the upstream side of the weir. Undersluices are separated from main weir by a *divide wall*. A *fish ladder* may be provided near the undersluices. There may be *guide banks* on the upstream and downstream sides of the weir towards both of its flanks. In continuation of the upstream guide banks, there may be river *flood embankments*. In alluvial soils, *silt excluder* may be provided in the pocket on the upstream side of undersluices and just in front of the main canal head regulator. The head regulator of main canal and the *silt ejectors* (or, main canal head escape if provided in the head reach of main canal) also come under the item 'head works' of the scheme. Water will be diverted into the main canal by means of diversion weir; it will pass from the river through the main canal head regulator and

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Index plan for direct irrigation scheme  
**Fig. 2**
flow into the main canal. The main canal will serve the function of simply carrying this water through the irrigated area.

Index plan for storage irrigation scheme

**Fig. 3(a)**

From the main canal, a number of *branch canals* and/or *distributaries* take off to carry the water to various parts of
the irrigated area. The distributaries make the water available near the land to be irrigated. From distributaries, a number of water courses or field channels take off to convey the water on the individual fields of irrigated land through or along which they pass. This entire net-work of irrigation channels is called canal-system. The channels of canal-system have a number of canal masonry works constructed on them to help the proper distribution of water and proper functioning of channels. These canal masonry works may consist of regulation works, cross drainage works, inland navigation works, communication works and other miscellaneous works.

If the land brought under irrigation is likely to be damaged or has been damaged as a result of the introduction of irrigation, the necessary drainage works are constructed to check or control the damage.

15. **Storage irrigation scheme:** The items in this scheme will also be as in the scheme mentioned in article 14 above.

The head works called the storage head works [see fig. 3(a)] consist of a dam with reservoir outlet sluices, deep-seated sluices and spillway; the main canals take water directly from the reservoir, through their respective outlet sluices. There may be a fish ladder and a log chute provided at one flank of the dam. In case of some storage schemes [see fig. 3(b)], the irrigated area may be far away from the main dam site; in such cases, the head works will, in addition to the main dam and its appurtenant works, consist of a pickup weir constructed across the river on the downstream side of main dam (and a few miles away from it), at a point where the irrigated area begins. The main canal or canals will in such case take off from the upstream side of the pickup weir and the weir will have underslues at its flank near the head regulator of main canal on that flank. The head regulator of main canal will also come under the item ‘head works’.

The description of other items will be the same as in irrigation scheme of article 14.

16. **Miscellaneous irrigation schemes:** The scope of two major irrigation schemes has been described in articles
14 and 15 above. In this article, the scope of *minor* irrigation schemes like inundation canal irrigation scheme, bandhara irrigation scheme and subsoil water irrigation scheme will be given.

Index plan for storage irrigation scheme

*Fig. 3(b)*

In the inundation canal irrigation scheme, there are no head works across river. Other two items are the same as for irrigation scheme of article 14.

In bandhara irrigation scheme, the head works consist of a low solid diversion weir across a stream. At the flank of this weir (called bandhara), there are small weir scouring sluices near the point where the irrigation channel takes off from its upstream side. From the flank, and on the up-
stream side, a protective wall is provided at right angles to the alignment of bandhara. In some cases, main canal is the only irrigation channel and no other irrigation channels like branch canal and distributary are necessary. This main canal which is of the size of a watercourse or a distributary of major irrigation scheme, is made to run on the outer boundary of the irrigated area which lies between the stream and this main canal. The channel thus irrigates on one side only. The masonry works on this channel are rather crude.

Subsoil water irrigation scheme mainly consists of either an open well or a tube well with the necessary lifting device to lift up the water from the well. The well is dug or drilled on irrigated area itself. The water lifted up is applied on the land by means of small subsidiary watercourses. The question of waterlogging does not arise in case of well irrigation. Open wells are mostly private property. In Baluchistan, in some localities which are alive with underground springs, certain irrigation scheme consists of an inclined underground tunnel called Karez. The water at the downstream end of karez is available above ground level and is either carried by a channel directly to the land, or in some cases, it is first stored in a surface tank from where it can be taken by a channel to the field as and when required. In case of flowing artesian well, the water from the well-bore is available above ground and it can be conveyed, in a channel, to the nearby land.

A minor irrigation scheme may also be in the form of lift irrigation from a stream. The head works in this case may consist of a pickup weir across the stream and a pumping set to pump water from the pool created on upstream side of the pickup weir. The water so lifted is carried by a channel to the bordering land to irrigate it. This feature of irrigation is much prevalent in South India.
CHAPTER 11

WATER REQUIREMENTS OF CROPS

1. Introductory: In this chapter, we shall learn about the cropping seasons, the crops grown in each season and the amount of water required by each crop during its period of growth. For its full and successful growth, every crop requires proper warmth, proper moisture, proper agricultural soil, air and proper methods of cultivation. From this it is clear that in different seasons and different soils, different crops will grow. Heavy (i.e. retentive) soil is suitable for crops like sugarcane, rice, etc. requiring more water while light (i.e. sandy) soil is suitable for crops like wheat, gram, etc. requiring less water. Normal or medium soil (i.e. one having 11-20% clay content) is suitable for crops like cotton, maize, etc. requiring normal quantities of water.

2. Indian agriculture: Nearly 70% of the population of India is directly or indirectly connected with agriculture. The chief crops of India are rice, wheat, sugarcane, tea, cotton, jute, linseed, groundnut, coffee and rubber. There are two principal cropping seasons in north India. They are:

(a) Kharif season in which the crops are sown by the beginning of south west monsoon and they are harvested in autumn.

(b) Rabi season in which the crops are sown in autumn and they are harvested in spring.

The kharif crops are rice, jowar, bajri, maize, cotton, tobacco, groundnut, etc. The rabi crops are wheat, barley, gram, linseed, mustard, potatoes, etc. Kharif crops require about twice to thrice the quantity of water required by rabi crops.

In south India, however, rabi and kharif seasons are not quite distinct. In fact, there is no marked distinction
between the various seasons. By one gentleman, the climate of Madras is described as being eight months *hot* and remaining four months *more hot*. This emphasizes the fact that in south India there are no clear-cut Winter, Spring, Summer and Autumn seasons as they are in north India. In Bombay-Deccan there are five crop seasons as shown on page 26. In the remaining parts of India, there are three crop seasons, namely, Winter crop season, Hot weather crop season and Monsoon crop season.

The duration for which a crop is on the field is called the *crop period* of that crop. In the following table, some crops, their seasons and crop periods are given:

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Crop</th>
<th>Season of crop</th>
<th>Crop period of crop in months</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Middle Rice (a)</td>
<td>Winter</td>
<td>5(\frac{1}{2}) - 6</td>
</tr>
<tr>
<td></td>
<td>Early Rice (b)</td>
<td>Autumn</td>
<td>4 - 4(\frac{1}{2})</td>
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<tr>
<td></td>
<td>Late Rice (c)</td>
<td>Summer</td>
<td>2 - 3</td>
</tr>
<tr>
<td>2.</td>
<td>Wheat</td>
<td>Rabi</td>
<td>5 - 5(\frac{1}{2})</td>
</tr>
<tr>
<td>3.</td>
<td>Jowar (a)</td>
<td>Kharif</td>
<td>4(\frac{3}{4}) - 5(\frac{1}{2})</td>
</tr>
<tr>
<td></td>
<td>Jowar (b)</td>
<td>Rabi</td>
<td>4(\frac{3}{2}) - 5</td>
</tr>
<tr>
<td>4.</td>
<td>Bajri</td>
<td>Kharif</td>
<td>4(\frac{1}{2})</td>
</tr>
<tr>
<td>5.</td>
<td>Maize</td>
<td>Kharif</td>
<td>4 - 4(\frac{1}{2})</td>
</tr>
<tr>
<td>6.</td>
<td>Barley</td>
<td>Rabi</td>
<td>5 - 5(\frac{1}{2})</td>
</tr>
<tr>
<td>7.</td>
<td>Gram</td>
<td>Rabi</td>
<td>6</td>
</tr>
<tr>
<td>8.</td>
<td>Sugarcane</td>
<td>Perennial</td>
<td>12 - 15</td>
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<tr>
<td>9.</td>
<td>Groundnut</td>
<td>Kharif</td>
<td>4 - 5</td>
</tr>
<tr>
<td>10.</td>
<td>Cotton</td>
<td>Kharif</td>
<td>6 - 8</td>
</tr>
<tr>
<td>11.</td>
<td>Linseed</td>
<td>Rabi</td>
<td>5 - 5(\frac{1}{2})</td>
</tr>
<tr>
<td>12.</td>
<td>Jute</td>
<td>Kharif</td>
<td>6 - 7</td>
</tr>
<tr>
<td>13.</td>
<td>Mustard</td>
<td>Rabi</td>
<td>4 - 5</td>
</tr>
</tbody>
</table>

Out of the cropping systems used in India, one-crop system is common. Somewhere, mixed-cropping system
also exists according to which a farmer sows two or more crops together. Rice or wheat is usually grown under one-crop system. Millets, pulses, oil seeds and cotton are often grown under mixed-crop system. For good crop-yield, crop rotation is desirable. Other advantages of suitable crop rotation are: (i) less soil erosion (ii) better use of soil moisture.

3. Agriculture in Gujarat and Maharashtra States:
In India, these two States have the biggest area under jowar and bajri. Next in order of the extent of cultivation are cotton, tobacco, groundnut, rice, wheat, ragi, maize, barley, gram, sugarcane and oil seeds.

4. Duty and Delta: Each crop requires a certain amount of water after certain fixed interval of time, throughout its period of growth. The time that a crop takes from the instant of its sowing to that of its harvest is called its period of growth or crop period. The time between first watering of a crop at the time of sowing to its last watering before harvesting, is called base or base period of the crop and is usually expressed in days. Base period of a crop is thus slightly less than its crop period but for all practical purposes, both may be considered as equivalent. As the amount of each watering and the interval of watering (and hence the number of waterings) are fixed for each crop, the total quantity of water required by each crop is also fixed and is different for different crops. The depth of each watering is usually from 6 cm to 10 cm (2\(\frac{1}{2}\)" to 4") depending on the kind of crop. Thus, rice crop requires about 10 cm (4") depth of water after an interval of every 10 days during its crop period which is about 120 days. In all, after about 12 waterings, 120 cm (48") total depth of water must have been put on the rice land. This total depth of water, in inches, required by a crop to come to maturity is called its delta. Knowing the area under a crop and its delta, we can find out the amount of water, in c.ft., that must have been applied on that area to mature that crop. In case of above-said rice, if \(A\) acres is the area under rice, the total water used during crop period of 120 days = \(\frac{48 \times A}{12}\) i.e., 4\(A\) acre-feet (0.5 hectare-metre);
an acre-foot is a unit of volume and is equal to the amount of water obtained by flooding an area of one acre to a depth of one foot. One acre-foot = 10 × 66 × 66 i.e., 43560 c.ft. (about 1233 m³). Hence the amount of water applied on the above-said rice field = 4A × 43560 i.e., 174240A c.ft (4934 m³). Hectare-metre is a unit of volume and is equal to the amount of water obtained by flooding an area of one hectare to a depth of one metre.

Also, if one cusec (0.028 cumec) of water is supplied continuously to this rice field throughout the crop period of above-said rice, we will be able to mature about 60 acres (24 ha) of rice at the end of its crop period. In this case we say that the average duty of irrigation water for rice crop is 60 acres per cusec (about 850 hectares per cumec) on the field. Average duty of irrigation water for a crop is thus the maturing capacity of one cusec of irrigation water when it is supplied to the crop continuously throughout its crop period or base period; or, it is the relation between the crop area matured and the quantity of water required to mature it. The place at which water is supplied, characterizes the duty. Thus, in the above case, water is supplied on field and hence duty is said to be at or on field. To express duty correctly and completely in the above case, we must say that the duty of irrigation water for rice crop is 60 acres/cusec on the field, the crop period being 120 days. This water supplied on the field is equal to the amount of water actually used by the crop and the reasonable and unavoidable losses of water on the field. From duty for a crop, we can also find out the amount of water supplied. Thus in the above case, the total quantity of water supplied on the field to 60 acres of rice = 120 × 24 × 60 × 60 c.ft. Hence, total water supplied to A acres of rice will be = \( \frac{A}{60} \times 120 \times 24 \times 60 \times 60 \) c.ft. = 172800A c.ft., which is practically the same as worked out from delta for the crop. The trifle difference between the two quantities is due to the fact that, corresponding to a delta of 48", the duty for rice will be 59.4 and this figure has been rounded to 60 while making the above calculations. Thus, from duty or delta for a crop, we get an idea of the amount of water required by the crop.
It has already been said in chapter I that the water from its source flows into main canal and from main canal into branch canal if any, or else into distributary. Where there are branch canals, it flows from branch canal into distributary and finally, from distributary, it flows into watercourse which carries water to the field. While the water flows into these irrigation channels, there are losses of water due to evaporation from water surface and, absorption from the bed and sides of these channels. These losses are called transit or transmission or conveyance losses in canals.

Duty of water for above-said rice at the head of watercourse will be less than that on the field. This is due to the fact that as water flows from head of watercourse and reaches the field, there will be some transit losses. Because of these transit losses, if we want one cusec net on the field, we must admit more than one cusec at the head of watercourse, say 1.1 cusecs. Now 1.1 cusecs released at the head of watercourse throughout the crop period, bring to maturity same 60 acres; therefore one cusec released at the head of watercourse throughout the crop period, will mature $\frac{60}{1.1} = 54.5$ acres (22 ha). Duty of water for rice is thus 54.5 acres/cusec (about 772 ha per cumecc) at the head of watercourse, the crop period being 120 days. This duty at the head of watercourse is also called outlet duty.

Note: 1 Cumecc = 1 m³/sec. Plural of cumecc is cumeecs.

Following the same reasoning, duty at the head of distributary will be less than that at the head of watercourse; duty at head of branch canal will be less than that at the head of distributary and finally, duty at the head of main canal will be less than that at the head of branch canal. The place at which duty is reckoned has thus effect on its value.

Duty when expressed as acres per cusec is sometimes called flow duty and this is the usual way of expressing it in the direct irrigation.

In storage irrigation also, duty can be expressed as acres/cusec. There is, however, another method of expressing it. Thus, it is usually expressed as so many acres per
one million c.ft. of water available in reservoir; this means that every one million c.ft. of water available in reservoir will mature so many acres of the crop under consideration. Such duty is sometimes called quantity duty. As an example, the quantity duty for wheat may be, say, 8 acres per one million c.ft. (about 115 hectares per million cu m) of that water which forms the available storage in reservoir. Quantity duty can be converted into flow duty from the relation, one acre/million c.ft. of \[ \text{available storage in reservoir} \] = 12 acres/cusec when the base period is 140 days.

Note: In Metric system, quantity duty is expressed as so many hectares per one million cubic metres of available water in the storage reservoir.

5. Factors affecting duty: Duty of irrigation water depends on the following main factors:

(a) Kind of crop: Different crops require different quantities of water and hence the duties for them are different. Duty of water for a crop requiring more water is less and vice versa. Thus, duty of water for rice is less than the duty of water for wheat.

(b) Season: Losses of water vary according to season and its climate. Hence the duty, truly speaking, varies from season to season and from month to month in the same season. The figures for duty which we express ordinarily are however the average figures considered over the whole crop period.

(c) Rainfall: If some of the rain falling directly on irrigated land is useful for growth of a crop, so much less irrigation water will be required to mature that crop. More the useful rainfall, less will be the requirement of irrigation water and consequently, more will be the duty of irrigation water. Hence, while fixing the duty of irrigation water for crops in area proposed to be irrigated, the statistics of rainfall (which proves useful for irrigated crops) are first taken. From the above description, it is clear that the total water requirement of an irrigated crop may be met partly by irrigation water and partly by useful rainfall falling directly on the irrigated area. Useful rainfall is that rainfall which falls in required quantity and when water is actually required by the crops. Only such rainfall serves the same purpose as that served by irrigation water.
(d) Nature of soil: If agricultural soil is very porous, there will be more loss of water due to absorption and hence the duty of water will be less. There is more loss of water in light soils than in heavy soils.

(e) Methods of cultivation: If the methods of cultivation (including tillage and irrigation) are faulty and entail unreasonable waste of water, duty of water will be less. If on the other hand the cultivator is economical in the use of water, duty will be more. This point is very important and therefore cultivator should be trained to use irrigation water fruitfully.

6. Importance of duty figures: Knowledge of duty of water for crops serves the following purposes:

(i) It helps in the design of irrigation channels proposed in an irrigation project. Also, knowing the amount of water available at the head of main canal and the overall duty (i.e. duty for mixed crops) at the head of main canal, we can have an idea of area that can be irrigated from the available water.

(ii) It helps to check efficiency of the working of a canal system. From the area actually matured by canals in existence, we can come to know whether the area actually matured is as proposed in the project or not: and, if not, why so?

7. Relation between duty and delta: If duty or delta for a crop is given, the other can be found out from the following relation connecting the two:

\[ \Delta = \frac{B}{D} \times 1.98 \]

where \( \Delta \) = Delta for crop in feet, reckoned at a place.

\( D \) = Duty for this crop in acres/cusec, reckoned at the same place, and

\( B \) = Base period of this crop in days.

Thus, given the delta for rice as 48" and base period as 120 days, we have,
\[
\frac{48}{12} = \frac{120}{D} \times 1.98
\]
i.e. \[
4 = \frac{120}{D} \times 1.98
\]
or \[
D = \frac{120 \times 1.98}{4}
\]
\[
= 30 \times 1.98
\]
= 59.4 acres/cusec, which is the duty corresponding to a delta of 48", base period being 120 days.

In Metric system, \( \Delta = \frac{B}{D} \times 8.64 \) metres = \( \frac{B}{D} \times 864 \) centimetres. Here \( D \) is in hectares per cusec and \( B \) is in days.

8. **Delta for some crops**: Below are given the average deltas for some crops. This delta given below shows the total water requirement of a crop; the irrigation water requirement may be something less, depending on the amount of useful rainfall. Delta on the field is inclusive of losses on the field.

<table>
<thead>
<tr>
<th>No.</th>
<th>Crop</th>
<th>Delta on field, in cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rice</td>
<td>120 cm (48&quot;)</td>
</tr>
<tr>
<td>2</td>
<td>Sugarcane</td>
<td>120 cm (48&quot;)</td>
</tr>
<tr>
<td>3</td>
<td>Lucerne</td>
<td>90 cm (36&quot;)</td>
</tr>
<tr>
<td>4</td>
<td>Tobacco</td>
<td>75 cm (30&quot;)</td>
</tr>
<tr>
<td>5</td>
<td>Garden fruits</td>
<td>60 cm (24&quot;)</td>
</tr>
<tr>
<td>6</td>
<td>Cotton</td>
<td>50 cm (20&quot;)</td>
</tr>
<tr>
<td>7</td>
<td>Vegetables</td>
<td>45 cm (18&quot;)</td>
</tr>
<tr>
<td>8</td>
<td>Wheat</td>
<td>30 cm (12&quot;)</td>
</tr>
<tr>
<td>9</td>
<td>Maize</td>
<td>25 cm (10&quot;)</td>
</tr>
<tr>
<td>10</td>
<td>Fodder (green oats)</td>
<td>22.5 cm (9&quot;)</td>
</tr>
</tbody>
</table>

9. **Crop seasons in Bombay-Deccan**: In the following table are given the crop seasons in Bombay-Deccan, their period or duration, usual crops grown in each season,
the average duties of crops at the head of main canal and the normal interval after which the watering should be given to the crops.

<table>
<thead>
<tr>
<th>Name of crop season</th>
<th>Period of crop season</th>
<th>Usual crops grown in crop season</th>
<th>Normal watering interval in days OR Irrigation frequency</th>
<th>Av. duty at head of main canal, in acres/cusec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hot weather</td>
<td>15th Feb. to 14th June</td>
<td>Fodder crops</td>
<td>15 to 20</td>
<td>60 to 70</td>
</tr>
<tr>
<td>2. Monsoon</td>
<td>15th June to 14th Oct.</td>
<td>(i) Bajri, Makai, Mug, Tur, Udid, etc.</td>
<td>20 to 30</td>
<td>180 to 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ii) Cotton</td>
<td>20 to 30</td>
<td>80 to 85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(iii) Rice</td>
<td>10 to 12</td>
<td>40 to 45</td>
</tr>
<tr>
<td>3. Rabi</td>
<td>15 Oct. to 14th Feb.</td>
<td>Wheat, gram, linseed, jowar</td>
<td>20 to 30</td>
<td>120 to 150</td>
</tr>
<tr>
<td>4. Eight months</td>
<td>15th June to 14th Feb</td>
<td>Onions, chillies, brinjals, rice, groundnuts, cotton, tobacco, tur, garlic</td>
<td>10 to 12</td>
<td>80 to 100</td>
</tr>
<tr>
<td>5. Perennial</td>
<td>12 months</td>
<td>(i) Sugarcane</td>
<td>10 to 12</td>
<td>40 to 45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ii) Pan gardens e.g. water melon</td>
<td>10 to 12</td>
<td>80 to 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(iii) Fruit trees, lucerne, vegetables</td>
<td>10 to 12</td>
<td>50</td>
</tr>
</tbody>
</table>

Note: 1 acre/cusec = 14.16 hectares per cumecc.
CHAPTER III

HYDROLOGY

1. Introductory: In its broad sense, hydrology deals with the behaviour and distribution of water in atmosphere and on earth. Engineering hydrology deals with the distribution and behaviour of water on earth. In its ordinary sense, hydrology is a science regarding rainfall, rainfall losses, surface runoff and other water surveys. In this chapter, therefore, description about the amount, distribution and nature of rainfall will be given. This chapter will also treat rainfall losses, surface runoff (annual or seasonal) and the maximum rate of surface runoff.

2. Sources of irrigation water: As already said in Chapter I, river water comes either from rainfall or from the melting of snow or from both. Rainfall and snowfall are known as precipitation from clouds. In the last chapter, we learnt about the water requirements of crops; in this chapter we shall learn as to how much water will be available at a particular point of the course of a river. Knowing the two, we can cut our coat according to the available cloth.

It has been estimated that the total quantity of water which annually flows down the rivers of India is about 1360 million acre-feet (i.e. 168 \times 10^6 hectare-metres). Out of this, only 450 million acre-feet (i.e. 56 \times 10^6 ha-m) is available as usable irrigation water.

3. Rainfall and runoff: Rainfall on an area during a certain interval of time (i.e. day, month, season or year) is expressed as so many inches of water-depth over the entire area. We can therefore find out its quantity, in cubic feet, if we know the area on which it falls. In Metric system, rainfall may be shown as so many centimetres of water depth over the area. A portion of this total rain water falling on the area is lost due to evaporation and a part due to absorption. The latter part percolates through the surface soil and goes underground. It flows through the subsoil strata
and, lower down the above-said area, it may come up above ground in some cases by seepage. The losses due to evaporation, absorption and some other causes (e.g. interception by vegetation on the area and by depressions on the area) are called the *rainfall losses* and are expressed in inches (or, centimetres) of water-depth over the entire area of rainfall. The difference between rainfall and rainfall losses is called the *surface runoff* or *surface flowoff* or *rainfall excess* and is expressed as so many inches (or, centimetres) of depth of water over the entire area of rainfall. This runoff flows down from surface of the area in form of small drains, and streams which join to make a river. The flow of surface runoff in a stream or river is called *stream flow* or *flood flow*. The ratio of runoff from an area to the rainfall on that area is known as *runoff coefficient*. If we consider the total stream flow at any point on the course of a stream or river, it must have come as surface runoff from an area starting from this point and lying on the upstream side of this point. Such an area from which the rain water drains to this point is called *catchment area* or *drainage area* of the stream or river for that particular site on the stream or river. This area is sometimes called *water-shed* and is the area within water-shed line which is on the upstream side of the site, and which starts at the site and closes also at the site. The total amount of water passing a site during a certain period is called *yield of the catchment* during that period. The yield of a catchment consists of the total amount of surface runoff (known as direct-runoff) and the seepage water, if any, coming up from subsoil on the upstream side of the site.

The rain water which percolates below ground is known as infiltration water. The infiltration may be shallow or it may be deep. Shallow percolation water is likely to come up as seepage water.

4. **Rain gauges**: *Rain gauge* is an instrument for measuring the rainfall, in inches (or, centimetres), falling on an area during an interval of time. The extent of above-said area will be that which is in the charge of a rain gauge. There are two types of rain gauges, viz.
(a) Non-recording rain gauge.

(b) Recording rain gauge.

Non-recording rain gauge is more common in India and the one that is most used in India is called the *Simon's rain gauge* and is shown in fig. 4. It is fixed at about ground level on a site which is quite level. Rain gauge should be at least 30 metres (100') away from obstructions like trees, houses, etc. Every day, at 8.00 a.m., the measurement of rain water collected in the receiving bottle of rain gauge is taken and the rainfall of the last 24 hours is recorded as the rainfall of the day on which the observation is taken. This is called *daily rainfall* on the area in the charge of rain gauge and in the centre of which it is fixed. The receiving bottle (which is of 3" to 4" diameter) of rain gauge can hold about 10 cm to 12.5 cm (4" to 5") of rainfall; hence, if on any day there is a heavy rainfall, the observations during 24 hours must be taken 2, 3 or more times if necessary so that the bottle may not overflow before any such observation is taken. The
last observation should be at 8.00 a.m. and the total of all observations during the last 24 hours is taken as rainfall of the day of last observation. From daily rainfall, the monthly rainfall in inches (or, centimetres) and the yearly rainfall in inches (or, centimetres) are calculated for that rain gauge station. Rain gauge stations should be evenly distributed over the catchment area for which rainfall is to be found out. In plain country, about 50 sq miles (i.e. 130 sq km) of area may be in the charge of one rain gauge. In uneven and hilly country, rain gauges may be nearer and may be provided at all necessary points so that the rainfall registered by them may be truly and correctly representative of the entire area. The rainfall records are maintained by one or more of the following departments:

Meteorological department, P.W.D., Agricultural department, Revenue department, Forest department.

Recording rain gauge is also called an integrating rain gauge. This rain gauge has an automatic mechanical arrangement consisting of a clockwork, a drum with a graph paper fixed round it and a pencil point in contact with the graph paper to make a mark on it. Rainfall gets automatically marked on the graph paper from where it can be read. Another advantage of this type is that not only we can read the rainfall after any duration of time (in hours) but, at any instant, we can also find out the rate of rainfall or the intensity of rainfall. We can also work out this intensity in inches (or, cm) per hour, inches (or, cm) per 6 hours, inches (or, cm) per 12 hours and so on. Also, this rain gauge can register rainfall for a fortnight and is therefore of immense use in places of difficult access, as in hilly areas.

Note: (i) For measurement of snowfall, recording and non-recording snow gauges are used, the latter type being common. Also snow surveys are done to measure snowfall. Snow survey is useful in estimating the runoff which can be expected due to the melting of snow in hot weather. In India, snow surveys are undertaken, by means of snow samplers, in the months of March or April i.e. just before the snow starts melting.

(ii) If a rain gauge is at high altitude, its rain-catch will be less than the actual rainfall due to the effect of strong wind at high altitude. There are formulae to correct the collected rain-catch for altitude so as to find out the actual rainfall at that rain gauge station.
(iii) In hilly places, which are not easily accessible, non-recording rain gauge of greater rain holding capacity may be used.

(iv) If rainfall is 0.1" (i.e., 0.25 cm) per hour, it is said to be of light intensity. If it is 0.1" to 0.3" (i.e., 0.25 to 0.75 cm) per hour, it is said to be of moderate intensity. If it is more than 0.3" (i.e., 0.75 cm) per hour, it is said to be of heavy intensity.

5. Definitions: In India, rainfall cycle is said to be of about 35 years; hence to get an average idea of rainfall at any rain gauge station, the mean of yearly rainfall for at least 35 years should be found out. This mean is called the average annual rainfall at this rain gauge station. When we talk of rainfall at any place, we usually refer to this average annual rainfall which is also called the normal yearly rainfall or only rainfall at that place. If the yearly rainfall at a place for a number of years be studied, it will be found that the yearly rainfall of various years deviates (or is different) from the average annual rainfall of the place. The year in which rain-fall is less than average annual rainfall, is called bad or subnormal or deficient year and conversely the year recording more than the normal rainfall is said to be a good year. A year having rainfall equal to the normal one is called normal or average year. For every place, there will be some good, bad and normal years of rainfall. Normally, the number of deficient years is slightly more than the number of good years. The maximum annual rainfall (of any good year during a period of 35 years) at a place may be about 1.24 to 2.54 times the normal rainfall and the minimum annual rainfall (of any bad year during 35 years) at a place may be about 0.27 to 0.78 times the normal rainfall at that place. The mean of yearly rainfall of about 10 to 12 consecutive bad years (during a period of 35 years) at a place is called the rainfall of average bad year at the place. Its value is from $\frac{2}{3}$ to $\frac{3}{4}$ of the normal rainfall of the place. The ratio of rainfall in a particular year to the normal rainfall is known as the index of wetness for that year.

Note: If the deficiency of rainfall in a particular year is 30 to 45% (below normal), it is known as large deficiency. If it is 45 to 60%, it is known as serious deficiency. If it is more than 60%, it is known as disastrous deficiency and is to be feared for its bad consequences.

6. Characteristics of Indian rainfall: In tropical countries, the rainfall at a place varies greatly in intensity at
any time, in total amount during a period and in its frequency or periodicity; also, it varies from place to place of the country. The rainfall thus varies with regard to time and place of fall.

The chief characteristics of rainfall in India are its unequal distribution throughout the seasons, its still more uneven distribution over the surface of the country and, finally, its frequent liability to partial or in some cases complete failure. In major portion of India, most of the precipitation is during the south-west monsoon season; in south India, however, most of the precipitation is due to north-east monsoon. The average annual rainfall varies from 1150 cm (460") in Assam to as low as 12.5 cm (5") in extreme north-west part of Rajasthan. It is the yearly variation and the deficiency of rainfall that stress the necessity and importance of irrigation in India.

Rainfall is ordinarily more at a place of greater geographical latitude and greater altitude. It is also more at a place which is near sea, high mountains and forests.

7. Isohyets: Isohyet is a line, on a rainfall map, joining places having the same average annual rainfall. From these isohyets or isohyetals marked on the rainfall map of a country, we can get, at a glance, an idea of the average annual rainfall at any place of the country. The isohyets of India are shown in fig. 5.

8. Runoff or Flowoff: The runoff in a year is called annual runoff. It is expressed either in inches of water-depth over the entire catchment or, in c.ft. if the area of catchment is known. It gives an idea about the amount of water that is available for storage by constructing a dam across a river at a particular site along the course of the river. Following are the main factors which affect the runoff from a catchment:

(a) Yearly rainfall at various places on the catchment: Greater the rainfall, greater will be the runoff.

(b) Season of rainfall and the condition of ground at the time of rainfall: There is greater rainfall and there-
fore greater runoff during certain time of a year. Also, if at the time of rainfall the ground is parched and dry, rainfall losses will be more and consequently runoff will be less.

(c) Characteristics of catchment, e.g. its slope, porosity, presence of depressions and vegetation on catchment, the climate on catchment: Greater slope results in less percolation loss and more runoff. Greater porosity of surface soil, more depressions and more vegetation on catchment or higher temperature on catchment result in more losses and the subsequent less runoff.

(d) Area of catchment above the site under consideration: Greater the area of catchment, greater will be the runoff.

Annual yield of a catchment = annual runoff + yearly up-seepage from subsoil, if any.

9. Average annual runoff: Average annual runoff of a catchment is the mean of the annual runoff for a period of 35 years.

10. Determining the average annual runoff: Following are the usual methods for determining the average annual runoff of a catchment:

(a) From yearly rainfall records for all the rain gauge stations on the catchment for a period of at least 35 years: From these figures, the average annual rainfall on the entire catchment is calculated. Knowing the coefficient of runoff, the average annual runoff of this catchment is found out. Here it is assumed that the entire catchment area is of same character and hence, one coefficient of runoff is used. If the different portions of a big catchment have different runoff characteristics, a separate coefficient of runoff will be taken for each such portion and the runoff calculated separately for each portion and all runoffs added to get the runoff of the entire catchment. This method is not reliable and may be used only for small catchments to get a rough idea of runoff.

(b) By actual gauging of a stream or river flow every day at the site of proposed dam and finding the yearly runoff: This is the best method and if records of actual gauging at
that site are available for at least 35 years, the average annual runoff can be accurately calculated. However, such records are not available for many sites in India where the gauging is usually started after a site has been actually chosen for a proposed dam and while the project is actually in hand. In such case also, it is advisable to get the idea of actual yearly runoff for even a few years while the project is in hand. From the actual yearly runoff for a few years and the corresponding annual rainfall for these years together with the yearly rainfall figures for at least 35 years, a fairly good (though not accurate enough) idea of average annual runoff can be had.

Gauge for registering flood levels

**Fig. 6(a)**

Gauge post

**Fig. 6(b)**

In addition to a gauging site, a few gauges may be fixed (see fig. 6), preferably at the gauging site, to record water levels in the river. These water levels are plotted against the corresponding discharges (obtained by actual gauging every day), to get the gauge-discharge curve. From this
curve, a rough idea of discharge at the site can be formed, on any day, by simply knowing the water level in the river on that day. This, of course, is true when the bed and sides of river are not subject to any marked erosion and silting. Instead of ordinary gauges, nowadays, automatic level recorders are used to note automatically the level of water at any instant. An automatic level recorder is fixed in a masonry gauge-well near river bank.

(c) By runoff formulae: Such empirical formulae are given by C. C. Inglis and by A. N. Khosla.

(i) Inglis’ formula for Bombay-Deccan catchments:

For ghat areas, \( R = (0.85P - 12) \)

where, \( R \) := Average annual runoff, in inches, from catchment.

\( P \) := The corresponding average annual rainfall or precipitation, in inches, over the entire catchment.

For non-ghat areas, \( R = \left( \frac{P - 7}{100} \right) \cdot P \)

where, \( R \) and \( P \) have the usual significance.

(ii) A. N. Khosla formula:

\( R = (P - t + C) \)

where, \( R \) := Average annual runoff in inches.

\( P \) := The corresponding average annual precipitation in inches.

\( t \) := Mean annual temperature in °F on the entire catchment.

\( C \) := A constant depending on the factors that affect the surface runoff from catchment.

(d) W. L. Strange’s runoff curves for old Bombay State catchments:

These curves are for good, average and bad catchments and are shown in fig. 7. The runoff is shown as percentage of rainfall. A good catchment is one which has got good runoff qualities and hence, for the same rainfall on it,
it gives more runoff. For the same kind (i.e. good, bad or average) of catchment, greater the rainfall more is shown the runoff percentage. These curves are, truly speaking, corresponding to the average south-west monsoon rainfall and not corresponding to the average annual rainfall; but in old Bombay State, nearly 90% of rainfall is during the period of S.W. monsoon and it will not be much erroneous to find the runoff of a catchment, from these curves, corresponding to average annual rainfall figure for this catchment.

Strange’s runoff curves for old Bombay State catchments

**Fig. 7**

11. **Gauging of river flow:** In method (b) of article 10 above, it has been said that this method is the best and should be used where practicable to get a good and exact idea about runoff.

For gauging purpose, a gauging site is laid out at the proposed dam site as shown in fig. 8(a). A length along the course of river, called gauge length or gauge run, is demarcated for this purpose. In the centre of this gauge run, a rope or cable is stretched across the stream or ordinary-size river, hanging high above the maximum water level in the river. Marks at fixed intervals are made on this rope to help in dividing the water width of river into a number of parts (usually 8 to 10) of same width. The depths of water in river at points exactly below these marks are taken with
a sounding pole if depth of water is less than 3 m (10 ft) and with a sounding cable if depth of water is more than 3 m. In fig. 8(b), the water width of river has been divided into 8 equal parts, thus dividing the water section of river into 8 compartments. Knowing the depths of water at the beginning and end of each compartment, the cross-section area of that compartment can be found out by treating the compartment approximately as a trapezium. Next, mean velocity

![Diagram of gauging station](image)

**Fig. 8(a)**

![Diagram of cross-section of river](image)

**Fig. 8(b)**

Cross section of river at position (2) of fig. 8(a)

of water in each compartment is determined by means of either a surface float or a velocity rod (also called rod float) or a current meter. The first two are usually used when depth of water is less than 1.5 m (5 feet). For depths above 1.5 m, current meter is more accurate and reliable. The discharge (i.e. rate of flow) through each compartment can then be found out by multiplying the area of compartment
with the mean velocity of water in that compartment. By summing up the discharges so found for all the compartments, we get the discharge passing through whole water-section of the river. The surface float and velocity rod are shown in fig. 9, while the Price current meter is shown in fig. 10. This type of current meter is common in India.

![Surface float and Velocity rod](image)

**Fig. 9**

When a surface float or a velocity rod is used, two more ropes, marked like the first rope, are stretched across the stream at the beginning and end of the gauge-run. At the beginning of gauge-run, a man goes wading in the stream and releases a surface float or a velocity rod at the centre of a compartment. Time taken by this float or velocity rod to reach the centre of same-numbered compartment at the end of the gauge-run is noted. Knowing the length of gauge-run, the velocity with which the surface float or the velocity rod has travelled is found out. In case of surface float, this result gives the surface velocity of water along that length and is taken as uniform from beginning to end of that length. It, therefore, can be taken as surface velocity of water in compartment of the same number at the centre of the gauge-run. This surface velocity is converted into mean velocity by the formula, \( v_m = 0.85 \, v_s \, \text{ft/sec} \), where \( v_m \) and \( v_s \) denote the mean and surface velocities respectively. In case of velocity rod, the result gives directly the mean velocity of water in the compartment.
In case of current meter, the meter is lowered from a boat or launch stationed in the centre of each compartment at the centre of the gauge-run. Meter is then lowered in water (with its wheel facing the current of water) at a depth below the water level equal to 0.6 times the depth of water at the position of boat. The observation to take the mean velocity is started and $v_m$ calculated from the rating formula of meter supplied by the manufacturer. An alternative is to take the velocity at 0.8$d$ and also at 0.2$d$ below free surface. Average of these two velocities will give mean velocity.

![Diagram of Price current meter](image)

**Price current meter**

Fig. 10

A surface float is merely a piece of wood. A velocity rod is a wooden rod of about 2.5 cm (1") diameter weighted at its bottom so as to float in vertical position. Its length should be such that its depth immersed in water should be about 0.94 times the depth of water at the centre of compartment and while floating, its top should be about 3.75 cm to 5 cm (1.5" to 2") above the water surface so that it can be seen floating. Thus, a set of velocity rods of different lengths is necessary.
The essential parts of a current meter are: a horizontal wheel in front carrying the cups, a tail vane, a counterweight at bottom to keep the meter steady and a device to record the number of revolutions of the horizontal wheel due to velocity of water. In deep water, current meter is suspended from a cable. The rating formula is usually in the form, 

\[ v_n = (a + bN) \text{ ft/sec}, \]

where \( a \) and \( b \) are constants of the meter and \( N \) is the number of revolutions per second for the current meter and is found from the observation taken at each section.

In case of very wide rivers, where it is not practicable to stretch a wire rope across the river, two theodolites (one from each bank at the gauging site) are used to help in locating the centre of each compartment. The man in boat or launch will align himself (by moving the boat or launch) till he finds himself in the centre of compartment. At this instant, he will take the depth of water and will also lower the current meter in water to take the mean velocity observation.

In case of small stream, notch or weir may be constructed across the stream to find the discharge of stream. From the average daily discharge found as shown above, monthly and yearly discharges can be calculated.

12. **Maximum rate of runoff**: The intensity of rainfall on catchment varies from time to time and hence, the rate at which the water begins to flow down from catchment also varies from time to time. The maximum rate at which the water comes down from a catchment is called its *maximum rate of runoff*. This occurs when all the factors producing it are simultaneously at their maximum effect. In India, as the Simon’s rain-gauge is mostly used, the maximum rate of runoff is expressed as so many inches of water-depth on the catchment, coming from the catchment in 24 hours. This volume of water divided by the number of seconds in 24 hours will give the maximum rate of discharge in cusecs passing at the site to which the catchment refers. This maximum rate of discharge at the site is also called the **high flood discharge** or the **intensity of maximum flood**. The **sufficient**
(but not extravagant) estimate of the high flood discharge is absolutely necessary for the safe design of certain irrigation structures like dam spillways, culverts, bridges, cross drainage works, pickup weirs and flood embankments. Following are the main factors affecting the maximum rate of runoff from a catchment:

(a) Maximum intensity of rainfall, its duration and frequency; also the area over which this maximum intensity of rainfall occurs.

(b) Size of catchment area relative to the area on which the maximum intensity of rainfall occurs: For the same intensity of rainfall, the flood discharge from a relatively small catchment is higher than from a relatively large catchment.

(c) Characteristics of the catchment area, e.g., its slope, porosity, presence of vegetation and depressions and, its shape: For the same intensity of rainfall, flood discharge from fan-shaped catchment is greater than that from elongated catchment of same area. The other characteristics affect high flood discharge in the same manner in which they affect the runoff.

(d) Direction of storm producing rain: If direction of storm producing rain is down the stream receiving the surface flow, it will produce greater flood discharge than when it is up the stream.

13. Determining the maximum rate of runoff: The following are some of the methods for determining the maximum rate of runoff from a catchment.

(a) From records of actual gauging of high flood discharge at the site of proposed work: Every year from actual daily gaugeings, the high flood discharge is picked out for that year. Records should be for at least 35 years, so that the possible value of maximum flood discharge can be selected from the 35 values of high flood discharge during 35 years. Such extensive records are however neither available nor economically feasible in India for any site on any river. Otherwise this method is most reliable and accurate.
(b) *From flood marks:* At the site, the maximum level up to which water may have risen in the past 35 years or so, must be known to some old villagers living near the site. These old persons can show the marks on river banks up to which this maximum water level ever reached. The cross-section of river at the site is taken with a level, it is plotted on paper and the water line corresponding to the level of highest flood mark pointed out by old villagers is drawn on the cross-section. From this, the area of water section, wetted perimeter and hydraulic mean depth are worked out. The bed slope of river at the site is found out by longitudinal levelling of river bed for a distance slightly upstream and also downstream of the site. Taking this bed slope to be approximately the same as the hydraulic slope at the time of high flood discharge, the mean velocity of water at the time of high flood discharge is found from Chezy formula or any other suitable formula for flow in open channels. High flood discharge will then be obtained by multiplying the mean velocity with the probable area of water section at the time of high flood discharge. This method gives rough idea about high flood discharge if the bed and banks of river are hard and stable as usually obtains in an undulating country.

(c) *From rainfall records:* In case of small catchments, daily rainfall records for at least 35 years may help to get a very rough idea about the probable high flood discharge expected to pass at the site.

(d) *High flood discharge formula:* There are certain empirical formulae known as flood formulae for the computation of high flood discharge. They give a general idea about the expected high flood discharge at the site. Their utility for large catchments is rather doubtful. Some of the flood formula are as follows:

(i) **Dicken’s formula:**

\[ Q = CA^n \text{ c.ft/sec} \]

where \( Q \) = High flood discharge in cusecs.

\( A \) = Catchment area in sq. miles and \( C \) and \( n \) are constants depending on factors affecting the high flood discharge; \( n = \frac{3}{4} \); average value of \( C = 825 \),
more value being for hilly catchments and vice versa. Also, for same type of catchment, greater the rainfall, greater the value of $C$ and vice versa. Value of $C$ should therefore be ascertained for each catchment according to the nature of catchment and the intensity of rainfall on it. Values of $C$ upto 1600 or so have been used. This formula is generally useful for catchments in North India.

(ii) Ryves’ formula:

$$Q = C A^n \text{ c.ft/sec}$$

where $Q$, $C$, $A$ and $n$ have usual significance. Here $n = -\frac{2}{3}$ and $C = 450$ and upwards, with less value for flat catchment and more for hilly catchment. As in Dicken’s formula, value of $C$ is to be ascertained for each catchment. Values of $C$ upto 670 or so have been used.

This formula is generally useful for catchments in South India.

(iii) Inglis’ formula for fan-shaped catchments in old Bombay State:

$$Q = \frac{7000A}{\sqrt[4]{A + 4}} \text{ c.ft/sec}$$

where $A$ = Area of catchment in sq.miles.

(iv) Nawab Jung Bahadur formula for Hyderabad-Deccan catchments:

$$Q = C A^{(0.92 - \frac{1}{14} \log A)} \text{ c.ft/sec}$$

where $C = 1600$ to 2000

and $A$ = Area of catchment in sq.miles.

This formula has wider use in India.

(v) W. P. Creager’s formula:

$$Q = 46 C A^{(0.894 + 0.048)} \text{ c.ft/sec}$$

where $C = 30$ to 100; lower values of $C$ are to be taken for ordinary floods and higher values for acute and intense floods and, $A$ = area of catchment in sq.miles.
(vi) W. E. Fuller's flood frequency formula:

\[ Q = C \cdot A^{0.8} \left\{ (1 + 0.8 \log T) \left( 1 + 2A^{-0.3} \right) \right\} \text{ c.ft/sec} \]

where \( C = 1.3 \) to 142.

\( A \) = Area of catchment in sq.miles.

\( T \) = Number of years after which such a high flood discharge is likely to re-occur i.e. such a high flood discharge occurs once in \( T \) years. \( T \) is called the recurrence period of flood, in years. It is reciprocal of the frequency of flood. Thus frequency of flood = \( \frac{1}{T} \). There are various empirical formulae for working out \( T \).

This formula is not used in India.

(c) Flood curves:

(i) Beale's and Whiting's curves for Bombay-Deccan catchments:

These are shown in fig. 11 from where, corresponding to the area of catchment, the high flood discharge can be read.

(ii) Recommendations by the Institution of Civil Engineers (London):

Failure of a reservoir embankment in 1930, led to the appointment of a committee by the Institution of Civil Engineers (London) to investigate the subject of 'Floods in relation to reservoir practice in British Isles'. This committee published an interim report in July 1933 after collecting and studying records of a number of past floods in British Isles.

In the report, the committee gave two flood curves (shown in fig. 12) connecting the intensity of maximum flood in cusecs per 1000 acres of catchment area with the catchment area expressed in units of 1000 acres. One of these two curves is for normal high flood discharges likely to occur fairly frequently and the other is for the abnormal high flood
discharges caused by occasional and exceptionally great intensity rainfall. These curves may be expressed by the general expression,

![Graph showing discharge in thousands of cusecs against catchment area in sq miles.]

Beale’s and Whiting’s flood curves

Fig. 11

![Graph showing flood intensity in cusecs per thousand acres against area in thousand acres.]

Flood committee’s curve

Fig. 12(a)
\[ Q = CA^n \text{ c.ft/sec} \]

where \( A \) is the catchment area in units of 1000 acres.

For normal high flood discharge,

\( C = 1250 \) and \( n = 0.60 \) in the above formula.

Abnormal high flood discharge may be about twice the normal high flood discharge.

The committee rightly pointed out that the subject of estimation of high flood discharge does not lend itself to rigid treatment by precise rules and it is therefore necessary to judge each particular case according to its own local conditions.

14. **Hydrograph**: Hydrograph is defined as a graph showing discharge, velocity or other feature of flowing water with respect to time. Discharge or velocity etc. is plotted as ordinate and time is plotted as abscissa. Thus, a discharge hydrograph shows the discharge of a river (at a particular site) as ordinate against the duration of this discharge as abscissa. The time period for discharge hydrograph may be hour, day, week, month, etc. Discharge hydrograph is commonly known as flood hydrograph or runoff hydrograph [see fig. 13(a)] for a particular storm falling on the catchment area which lies on the upstream side of the river-site under consideration. Such a storm on the catchment causes the above-said discharge (or flood flow) at this site.
of the river. Thus, the flood hydrograph has reference to a particular river-site.

The area under a flood hydrograph denotes the volume of water due to flood in that duration for which the flood lasts. From the flood hydrograph, we can also read the following:

(a) Rate of flood-flow, at the site, at any instant during the duration period of the flood.
(b) The total volume of flood-flow, due to that flood, upto that instant.
(c) The maximum rate of flow caused by that flow at a particular instant during the duration period of the flood.
(d) The rise and fall of the flood.

\[ \text{Discharge} \]

\[ \text{Run-off hydrograph} \]

\[ \text{Time} \quad \longrightarrow \]

fig. 13(a)

For a particular river site, the catchment area is divided and the figures for the rainfall and runoff for this catchment are collected. From this rainfall and runoff data, care should be taken to select such storms as are isolated and intense and as occur uniformly over the catchment; further, the duration period of these storms should preferably be from 6 to 12 hours. From these storms, the flood hydrographs are prepared and from these flood hydrographs, a hydrograph known as unit flood-hydrograph is prepared. A unit hydrograph [see fig. 13(b)] is defined as a hydrograph which represents one inch of runoff from a rainfall of some unit duration falling over the specified area of the catchment. This unit dura-
tion may be from 6 to 12 hours, the larger unit duration (between these two limits) being used for larger catchment areas. The use of unit hydrograph is to estimate the rate of flow and the volume of flood flow, for any other storm of unit duration (i.e. the duration used for unit hydrograph). The ordinates of the unit hydrograph and any other flood hydrograph of unit duration due to a storm will be in proportion to the rates of runoff represented by the unit hydrograph and this other flood hydrograph. Thus, with the help of unit hydrograph, we can prepare, in general, the other flood hydrographs for future storms on the catchment. In particular, we can prepare a design flood hydrograph (see fig. 14) which will give us an idea about the anticipated H.F.Q. and the volume of flood flow due to this H.F.Q.

This unit hydrograph method of developing the design flood hydrograph and thus predicting, with fair accuracy, the H.F.Q. is useful for catchment areas up to 5180 sq. km (2000 sq. miles). It may however be remarked that, since this method of finding H.F.Q. is a bit laborious, its use is justified only for the final design of important water control structures. It may also be pointed out that when there is no surcharge storage (i.e. flood absorption) at the site of the proposed dam, it is not necessary to know the rate of rise or fall of
flood and the volume of flood, along with the value of H.F.Q.; in such cases, therefore, the other methods of finding H.F.Q. will be quite useful. Where, however, the surcharge storage is of significance, it is necessary to develop the design flood hydrograph because such a procedure ensures the proper and safe design and operation of the water control structures like spillways, etc.

\[
\begin{align*}
\text{Discharge} & \rightarrow \\
\text{Time} & \rightarrow \\
\text{Fig. 14}
\end{align*}
\]

Note: (i) 1 cm runoff from one hectare = 100 cubic metres of water.
(ii) A flow of 1 cusec for 1 year = $31.54 \times 10^8$ cubic metres of

15. Choice of methods of computing H.F.Q.: In the table given below, are shown the various methods of determining H.F.Q. The choice of a particular method depends on the extent of catchment area and on the amount of accuracy required. It also depends on the data available for finding the H.F.Q.

<table>
<thead>
<tr>
<th>Catchment area in sq. miles</th>
<th>Suitable method of finding H.F.Q. coming from the catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) less than 1</td>
<td>(i) Rational method</td>
</tr>
<tr>
<td>(b) to 100</td>
<td>(ii) Overland flow hydrograph</td>
</tr>
<tr>
<td>(c) 100 to 2000</td>
<td>(i) Rational method</td>
</tr>
<tr>
<td>(d) more than 2000</td>
<td>(ii) Flood formulae and Flood curves</td>
</tr>
<tr>
<td></td>
<td>(iii) Flood frequency method</td>
</tr>
<tr>
<td></td>
<td>(iv) Unit hydrograph method</td>
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<tr>
<td></td>
<td>(i) Flood formulae and Flood curves</td>
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<td></td>
<td>(ii) Flood frequency method</td>
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<td></td>
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<td></td>
<td>(i) Flood formulae and Flood curves</td>
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<tr>
<td></td>
<td>(ii) Flood frequency method</td>
</tr>
<tr>
<td></td>
<td>(iii) Flood routing method</td>
</tr>
</tbody>
</table>
The description of flood frequency, unit hydrograph and flood routing methods is beyond the scope of this basic book. For definition of flood routing, see chapter on 'soil conservation and flood control'.

In rational method, H.F.Q. is found from the equation,

\[ Q = C \cdot i \cdot A \text{ cusecs} \]

where, \( C \) is run-off coefficient depending on the characteristics of catchment area. Its value ranges up to 1.

\( i \) is the rainfall intensity in inches/hour. Some formulae have been developed to find out \( i \).

\( A \) is the area of catchment in acres.
CHAPTER IV

STORAGE HEAD WORKS AND SURFACE STORAGE

1. Introductory: In this chapter, will be described storage head works and the method of storing runoff (from a catchment) or what is called the total flow of a river at a particular point on the river. By constructing an impervious high barrier or wall called dam across a river at suitable site, water gets collected in valley at the back of dam, forming a surface storage which is called an artificial lake. This is shown in fig. 15. If the storage is big, the lake is called a storage reservoir and when the storage is small, it is called a tank. A tank is thus a small storage reservoir. Surface storage serves many purposes, viz.,

![Diagram of Storage Reservoir with Masonry Dam](image)

Storage reservoir with masonry dam

Fig. 15

(a) Conservation of water-supplies during monsoon period to be used subsequently for irrigation, power generation and water supply of towns.

(b) Control of intense floods which otherwise entail loss of life and property.

This chapter, however, deals with the conservation of water for irrigation purpose only. Storage for one purpose only (e.g. for irrigation) is called single-purpose storage. Treatment of multi-purpose storage is beyond the scope of this book.
2. **Storage head works:** Storage head works consist of:

(a) Suitable type of dam across a river creating a lake, at its back, between it and the sides of the valley on its upstream side.

(b) Ancillary works of dam: They are,

(i) Surplussing work like spillway and/or flood sluices to dispose off the surplus water that cannot be safely stored in a lake. Spillway is therefore called the *safety valve* of dam.

(ii) Irrigation supply sluices or reservoir outlets (fitted with gates or valves) to take out the stored water through them.

(iii) Fish pass or Fishway, if any.

(iv) Log chute or Logway, if any.

(c) In some cases, in addition to the main dam, there may be a pickup weir with subsidiary storage at its back to feed the main canals which take off from upstream side of the pickup weir. Pickup weir is located a few miles downstream of the main dam.

3. **Lake basin:** Valley at the back of dam in which water gets stored is called the basin of lake or *lake basin*. Lake basin should be cup-shaped to ensure good storage for comparatively less height of dam. Deep basin ensures less loss due to evaporation and, the watertight bed and sides of basin entail less loss due to absorption. The basin should be of such area that the existing cultivated land submerged by the lake should not be more than 20% of the area proposed to be irrigated from water of this lake. Water in lake is stored upto a level known as *Full Lake Level* (F.L.L.); during floods, this water level may be allowed to rise to a certain maximum level called *Maximum Water Level* (M.W.L.) or *High Flood Level* (H.F.L.). Top of dam is kept above H.F.L.; the vertical distance between top of dam and H.F.L. is called *free board*.

4. **Storage capacity of lake:** Capacity of lake is expressed in million cubic feet (M.c.f.t) or sometimes in acre-
feet (A-ft.). The total quantity of water in a lake upto F.L.L. is called gross storage capacity of lake. The quantity of water from sill of the lowest set of supply sluices to F.L.L. is called live storage and the storage below this sill is called dead storage because it cannot be taken out and used for irrigation. Some of the live storage is lost due to evaporation and absorption; the balance water is called available storage or effective capacity of lake as this is the net water in the lake that can be diverted for irrigation. In old Bombay State, the S.W. monsoon season breaks in June and continues upto October. Irrigation year, here, therefore starts in October with the end of monsoon season and ends in June with the beginning of the next monsoon season. Irrigation water is taken from a lake during this so called irrigation year. It is desirable that at the end of irrigation year, there should be some storage in lake, above sill of the lowest set of irrigation sluices. This can be used for crops if the monsoon is a little late i.e. monsoon does not break in June. If the monsoon starts at the proper time, this water will be carried over to the next year’s supply in the lake. Such storage is therefore called the carryover storage and it protects crops against late monsoon.

*Note:* In Metric system, the capacity of lake may be expressed in million cubic metres or, in hectare-metres.

5. Evaporation and absorption losses in lake: Some water of lake is lost by evaporation from the water surface exposed to atmosphere from time to time. This loss depends on season, temperature at the site of lake, area of water surface exposed to atmosphere, humidity of atmosphere and the presence or otherwise of high winds. The absorption loss from bed and sides of lake basin is due to seepage and percolation. This loss depends on the porosity of basin and the depth of water stored. As it is not practicable to calculate evaporation loss and absorption loss separately, these losses are allowed for, together. The combined loss in a year due to evaporation and absorption from lakes in old Bombay State is roughly taken as 1.8 m (6 feet) on the mean area exposed to atmosphere during the course of irrigation year or, at the rate of 1.2 m (4 feet) on the area at F.L.L. Thus, the amount of water lost in a year will be equal to
\((A_m \times 6)\) c.ft. or \((A_f \times 4)\) c.ft. where \(A_m\) and \(A_f\) are the mean area and the area at F.L.L. respectively.

In case of lakes, the loss due to evaporation is more (about twice) in magnitude than that due to absorption.

6. **Sedimentation in lakes:** Runoff from catchment brings, with it, debris called *silt*. Silt consists of clay, loam, fine silt particles, coarse silt particles, fine sand, coarse sand, gravel and the floating matter called *drift*. The lighter silt may be in suspension in water and heavier silt rolls along the bed of river due to velocity of water. Heavier silt is therefore called the *bed silt*. As the water from catchment comes along river and enters lake, it brings with it the silt which may be partly in suspension and partly as bed-load. The heavier silt gets deposited near the upstream margin of lake and the lighter silt in suspension goes further towards dam and gets deposited near the dam. The deposit of silt on the bed and sides of a lake is called *sedimentation* in the lake. As the time passes on, more and more of lower portion of the lake, below sill of the lowest set of supply sluices, gets silted up. The dead storage is kept about 10% of the gross storage to allow this silting-up of the lake. Under no circumstances should the silt deposit be so heavy as to be above the sill of the lowest set of supply sluices for, in such case, the live storage gets affected. The factors affecting this sedimentation are:

(a) Catchment characteristics: e.g., its area, softness of its surface or otherwise, surface slope, temperature on catchment, presence of vegetation on catchment.

(b) Rainfall characteristics: e.g., its nature, intensity and season of fall.

Sedimentation in lakes can be controlled and reduced by,

(i) Making the soft and bare soil of catchment stable by *afforestation*.

(ii) Constructing *check dams* (see fig. 140) across streams which contribute to the water in the lake.

(iii) *Constructing contour trenches* (see fig. 138) on the steep and hilly slopes of catchment.
(iv) Not storing in lake the heavily silt-charged earlier flood water, if practicable.

7. Computing the storage capacity of lake:
The lake basin is contour-surveyed upto tentative H.F.L. at least, taking vertical contour interval as 3 m (10 ft). The areas within contour lines at these 10 ft. vertical intervals are found out by planimeter. The areas within contour lines at one foot (i.e. 0.3 m) vertical interval are calculated, treating the lake upto its H.F.L. as a frustum of a cone. Volume of water between every two adjacent one-foot-interval contour lines is found out by cone formula or prismoidal formula and the sum of such volumes (between every two adjacent contour lines at one foot vertical interval) upto tentative F.L.L. gives the gross storage of the lake. As an example, let the depth of water upto H.F.L. be 30 ft. and upto F.L.L. be 28 ft. The three contour lines which will be surveyed will be at R.Ls. 30, 20 and 10, taking the R.L. of H.F.L. to be 30. Area within these contour lines will be found by planimeter and those within contour lines at R.Ls 1, 2, 3, 4, \ldots\ldots 29, will be calculated. The volume of water between R.Ls. 0 and 1, 1 and 2, 2 and 3, 3 and 4, \ldots\ldots 27 and 28, will be calculated. Sum of these volumes will be the gross storage between R.Ls. 0 and 28. Similarly the live storage, the dead storage or, the storage between any two levels can be found out. The cone and prismoidal formulæ are as follows, the latter being more accurate:

(i) Cone formula:

\[ V = \frac{H}{3} \left\{ A_1 + A_2 + \sqrt{A_1 \times A_2} \right\} \text{ c.ft.,} \]

where, \( V \) = volume between two adjacent contour lines having \( A_1 \) and \( A_2 \) as areas, in sq.ft., within them.

\( H \) = vertical interval, in feet, between these two adjacent contour lines.

(ii) Prismoidal formula:

\[ V = \frac{H}{6} \left\{ A_1 + A_2 + 4A_m \right\} \text{ c.ft.,} \]
where, $A_1$, $A_2$ and $H$ have the usual significance.

and, $A_n$ = area within a contour line midway between the two adjacent contours.

A table is always prepared showing the live storage corresponding to the water at any level above sill of the lowest set of supply sluices. A curve is also plotted showing live storage at different levels of reservoir.

*Note:* In Metric system, the contour interval shall be in metres and the volume shall be in cubic metres.

8. **Fixing the height of dam:** The limiting factor for the irrigating capacity of a lake is either the catchment area or the proposed irrigated area. Since special attention is given to the selection of site of dam, the catchment area is usually the limiting factor. In such case, the catchment area for the dam site and its runoff in average bad year are determined. The live storage in the lake should be about 1.1 times the runoff of an average bad year. This implies that the lake will always be full in an average bad year and nearly so in year of most deficient rainfall. Find from the table of live storage that level of water in the lake which corresponds to this live storage. Such level fixes the likely F.L.L. The depth of maximum flood above F.L.L. is decided. This depth added to the F.L.L. gives the H.F.L. Adding a suitable value of free board to H.F.L., we get R.L. of top of the dam. The difference between R.L. of top of dam and R.L. of the deepest river bed at the dam site, gives the maximum height of dam superstructure that will be necessary to ensure the required storage. The area to be irrigated is then fixed, knowing the available water. If depth of dam foundation is decided, we can find out the total height of dam up to the natural foundation bed on which it rests.

9. **Fixing the site of dam:** While fixing the site of a dam, the following general considerations are kept in view:

(a) Suitable foundation-bed should be available at the site for cheap construction of dam.

(b) Materials of construction should be available at dam site or near it.
(c) Dam site should be connected with neighbouring towns by good lines of communication so that the construction may be cheap and may not present difficulties.

(d) Bed and the sides of lake basin should be fairly watertight and the basin should be preferably cup-shaped with flat bed and steep sides.

(e) The cost of dam to give the required storage should be minimum.

(f) The site should entail minimum overall cost of construction and minimum cost of subsequent maintenance.

(g) Spillway (i.e. the device for disposing off surplus water to downstream side of dam) should be safely and cheaply located in the dam or it may be separate from it.

(h) The site should ensure adequate capacity of lake created by it.

(i) The site should ensure less length of dam.

In the case of various types of dams, there will be some particular considerations also.

10. Kinds of dams: Following are the kinds of dams that have been constructed so far:

(a) Masonry dams and plain concrete dams: They are:

(i) Straight solid gravity dam: This may be either,

(i) a non-overflow dam i.e. storage dam usually called only dam, or,

(ii) an overflow dam. The top of (storage) dam is always above H.F.L., while the top of an overflow dam is below H.F.L.; hence, the latter dam is also known as storage weir or diversion dam. The storage weir may be with or without crest shutters on its top.

(ii) Single arch dam.
(iii) (i) Buttress dam called the multiple arch dam or arch-buttress dam.

(ii) The cylinder type or massive head type buttress dam.

(b) R.C.C. dams: The usual type under this head is called the slab-buttress dam. When this dam serves as an overflow dam, it is called a hollow dam or cellular dam.

(c) Earth dams: They are,

(i) Earth dam (rolled fill type).

(ii) Hydraulic fill dam.

(d) Rock fill dam.

(e) Steel dam.

(f) Timber dam.

Steel and timber dams are, in essence, the buttress dams. The earth dam and rock fill dam are sometimes called non-rigid dams as distinguished from other types of dams which are called rigid dams.

11. Choice of the kind of dam: The selection of the best kind of dam for a given site is a problem in both the engineering feasibility and cost of the work. Following considerations help to decide the kind of dam to be constructed to create a lake at a given site:

(a) Suitability of natural foundation bed and river banks at the dam site.

(b) Cross-section of river at dam site.

(c) Suitable site for location of spillway.

(d) Availability of the materials of construction.

(e) Length and height of dam.

(f) Importance of stored water.

(g) Overall cost of construction and the cost of subsequent maintenance.

12. Flood absorption capacity of a storage reservoir: In some cases, it is necessary to provide spill-
way of sufficient capacity to dispose off whole of the high flood discharge. This is so when the flood absorbing capacity (i.e. surcharge storage) of lake is small as compared to the total volume of maximum flood to be disposed off by the spillway. Flood absorbing capacity of a lake is the cubic contents of lake between its permanent F.L.L. and H.F.L. The crest of spillway is kept at permanent F.L.L. When the flood absorbing capacity is large, as is usual in case of reservoirs, a considerable portion of water due to maximum flood may be temporarily stored or absorbed or accommodated in the reservoir between its permanent F.L.L. and H.F.L., and hence, the spillway capacity to be provided in such case will be much less than the peak intensity of maximum flood. Thus, where the advantage of flood absorbing capacity of reservoir is taken, the spillway capacity required will be less than otherwise because the peak intensity of flood gets moderated while the flood passes through reservoir. To know whether the flood absorbing capacity of a lake can be utilized or not, we should have an idea of the volume as well as the peak intensity of maximum flood in addition to the cubic contents of lake between the spillway crest and the H.F.L. The peak intensity of maximum flood is also called high flood discharge. The property, possessed by a reservoir, of moderating or routing the intensity of flood is called the lag effect of the reservoir.

13. Types of spillway or surplussing work: Below are given the common types of spillways. The type adopted in each case depends mainly on the kind of dam and the intensity of high flood discharge to be disposed off:

(a) Weir-type spillway or Overflow spillway: It is usually located in a portion of dam itself and is called waste weir. Waste weir may also be quite separate from the body of dam. The waste weir may be with or without crest gates.

(b) Siphon spillway: It ensures a more close regulation of H.F.L. Its two sub-types are:

(i) Ordinary or common siphon. This is also called saddle siphon or, sometimes, hood siphon.

(ii) Volute siphon.
(c) Shaft spillway.
(d) Emergency spillway or Auxiliary spillway: This is also called the breaching section and is provided in case of important earth dams only.

14. Head water control: The head water or upstream water (i.e. water in lake) is controlled by:
(a) Supply-sluice gates.
(b) Spillway crest gates.

![Diagram of Supply sluice with gate](image_url)

*Supply sluice* is an outlet or opening pierced through the body of dam from its upstream to downstream side to allow the water from the lake to pass through it. These sluices are fitted with gates which, in closed position, rest on the sill (i.e. bottom) of the sluices as is shown in fig. 16.

When the sluices are to be opened to take out water, the gates are raised up. In case of great pressure-heads, the sluices are provided with valves instead of gates. The upstream end of outlet sluice is bell-mouthed upto the gate for smooth entry of water. From the gate to the outlet end,
sluice is usually of uniform cross-section. All sluice gates should be watertight, easy to operate quickly and should not be liable to get jammed by rust or debris.

The spillway is also, in many cases, provided with gates to control the flow of flood water from the lake. These gates also should be watertight, easy to operate quickly and should not be liable to get jammed by rust or debris.

15. Waste weir with crest-gates (i.e. controlled waste weir): When no gates are provided, the permanent (i.e. masonry) crest of waste weir is kept at F.L.L. During high flood, water level rises above F.L.L. upto H.F.L., thus flooding more basin of the lake. This flooding may be objectionable when the property in this flooded area (between F.L.L. and H.F.L.) is very valuable. The solution is to lower the permanent crest of waste weir and fit it with quick-acting shutters or automatic crest-gates. The top of the gates or shutters, in closed position, is kept at H.F.L.; as in fair weather, the water can be stored practically upto the top of gates, the F.L.L. has been thus virtually raised from the permanent crest of waste weir to the H.F.L., or in other words, there has been the assimilation of F.L.L. and H.F.L. Thus, in case of automatic gates or shutters, the storage between the permanent weir crest and the H.F.L. can be utilized during fair weather. In such case, the raised F.L.L. is also called the fair weather F.L.L. and is practically at H.F.L. In flood season, as soon as the water rises slightly above this fair weather F.L.L., the shutters or gates operate automatically and clear (i.e. open) the waste weir sluices, allowing the flood water to go out of the lake. Thus, the flood water is not allowed to rise much above fair weather F.L.L. and there is no submersion of extra area on upstream side during floods. Also, another advantage of crest gates is that, for the same F.L.L., the height required of a dam fitted with such weir crest gates will be less.

The suitable type and size of such crest gates used, depend on the following points:

(a) Gradual or abrupt rise of floods.
(b) Frequency of floods.
(c) Whether the H.F.L. is to be closely regulated or not.

In case of open or uncontrolled waste weir, after the water level rises upto F.L.L. (i.e. the permanent crest of waste weir), if any flood water comes from catchment into the lake a part of it will get stored temporarily into the lake and a part will go out i.e., there will be storage and outflow simultaneously. This will continue till the water level in the lake rises upto H.F.L. At this instant, the waste weir should be able to dispose off whatever flood water enters the lake i.e., the outflow should be equal to inflow. This condition may be for some time and when the inflow subsides, the water level in the lake will gradually come down, back to F.L.L. Thus, the water temporarily stored between F.L.L. and H.F.L. is gradually given out and the water level in the lake falls back to F.L.L.

In case of waste weir with automatic gates, the water gets stored upto the fair weather F.L.L. and if there is more inflow after this, the gates open suddenly and bring at once the flood absorbing capacity of reservoir into effect. This capacity is between the permanent crest of the waste weir and the fair weather F.L.L. which is practically the same as H.F.L. Flood sluices or deep seated sluices, if provided, also help to bring the flood absorbing capacity of reservoir into effect.

16. Types of spillway gates: The usual types of spillway gates are:

(a) Vertical lift gate or Draw gate: This may be,
   (i) Plain sliding gate.
   (ii) Roller gate: The roller gate may be a fixed roller gate or a free roller gate. The free roller gate is also called Stoney gate.

(b) Taintor gate (i.e. sector gate).

(c) Drum gate.

17. Gate hoist or gate operating gear: The non-automatic spillway gates are operated by a device which
is called the *gate hoist*. Following are the *usual* types of gate hoist:

- (a) Rack and pinion hoist.
- (b) Screw-steam hoist.
- (c) Drum hoist.
- (d) Hydraulic hoist.

The gate hoist can be worked by hand, electric motor or hydraulic pressure according to the type of gate hoist. The drum hoist may be one for each gate and is fixed on gate bridge or, there may be one travelling hoist on gantry, useful for operating a number of gates.

There are other gates called *automatic spillway gates* which operate automatically, depending on the level of water in the lake.
CHAPTER V

MASONRY AND CONCRETE DAMS

1. Introductory: In this chapter, only solid gravity dam of masonry and plain cement concrete will be treated. Single arch dam and multiple arch dam will be described in chapter VI.

2. Gravity dam: A gravity dam is a dam which resists the external forces (main force being the water pressure) by virtue of its dead weight. Solid gravity dam may be in one or more straight lengths to make its entire length or, its whole length may be slightly curved in plan, with convexity on the upstream side. The former is called a straight solid gravity dam and the latter is called a curved solid gravity dam. Straight lengths of dam are joined by smooth curves at their junctions when dam is not in one straight line.

3. Materials used for construction: A solid gravity dam may be constructed of:

(a) Uncoursed rubble masonry in hydraulic lime mortar or cement mortar. The upstream and downstream faces of the dam, for a thickness of about 1·5 m (5 feet) or so, are constructed in coursed masonry which is pointed in cement mortar. The upstream face may, further, be plastered to make it watertight.

(b) Cyclopean concrete with facings of coursed masonry. This is cheaper than uncoursed rubble masonry with coursed rubble facings.

(c) Plain cement concrete. This construction is cheapest and quick and is widely used nowadays.

The specific gravity of stone masonry of dam may be from 2·0 to 2·5, with an average value of 2·25. Specific gravity of plain cement concrete work may be taken as 2·25.

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4. **Low and high solid gravity dams:** A gravity dam is said to be *low* when its height, in feet, is less than the expression

\[ \frac{\lambda}{w(1 + s)} \]

where \( \lambda \) = the safe compressive stress allowable for the masonry (i.e. stone masonry or concrete) of the dam, in tons/ft\(^2\);

\( w = \) density of water in tons/ft\(^3\);

\( s = \) specific gravity of the masonry of dam.

A gravity dam is said to be *high* when its height is more than \( \frac{\lambda}{w(1 + s)} \) feet.

*Note:* In Metric system, if \( \lambda \) is in tonnes/m\(^2\) and \( w \) is in tonnes/m\(^3\), the expression \( \lambda = w(1 + s) \) will be in metres.

5. **Theoretical and practical profiles (i.e. cross sections) of a low solid gravity dam:** The *theoretical profile* of a low solid gravity dam is a right angled triangle with water face (i.e. upstream face) vertical, the apex or vertex of this triangle at H.F.L. and the base of triangle equal to \( \frac{h}{\sqrt{s}} \); here \( h \) is the depth of water from river bed to H.F.L. This profile is also called the *elementary profile* or *economical profile* because the material of such dam is stressed to its maximum safe compressive stress when reservoir is full and when reservoir is empty.

The *practical profile* is that which is provided in practice. The practical profile will, thus, have some free board and some top (i.e. crest) width as shown in fig. 17. Free board is necessary to keep the top of dam above H.F.L. and not to allow the water waves to over-top the dam. The minimum top width ‘\( a \)’ to be provided is equal to \( \sqrt{h} \), subject to the roadway requirements because the top of dam is used as road. Free board should be equal to \( 1\frac{1}{2}y_s \), subject to a minimum of 4 ft (1.2 m); here \( y \) is the height of wave in feet given by Stevenson’s formula which is as follows:

\[ y = 1.5F^{1/2} + 2.5 - F^{1/4} \]

where, \( F \) is the fetch in nautical miles. Fetch is the distance across open water through which wind acts to generate
the waves. Height of wave also depends on the velocity and duration of wind.

*Note:* 1 nautical mile = 1852 metres = 1.852 km = 6080 feet.

Theoretical and practical profiles of low solid gravity dam

*Fig. 17*

Due to the provision of free board and top width, the resultant force of the weight of dam and the water pressure falls outside the middle third of base of dam when reservoir is empty. To bring this resultant force back in the middle third, a little masonry is provided on the upstream side of the upstream vertical face of the dam as shown in fig. 17. The various other dimensions are also shown in the figure and are self-explanatory.

*Note:* Sometimes, free board is kept about 2 to 4% and top width is kept about 10 to 14% of the height of dam.

6. **Theoretical and practical profiles of a high solid gravity dam:** Upto the limiting height of low dam, viz. \( \frac{\lambda}{w (1 + s)} \), the material of dam is stressed practically
to its maximum allowable compressive stress. If the height of dam is increased beyond \( \frac{\lambda}{w(1-s)} \), keeping the principle of design the same as for low dam, the material will be overstressed and may fail by being crushed. To safeguard against this, the design of a high dam should be such that not only the resultant force should obey 'middle third rule', but simultaneously the material should not get overstressed. Also, at the heel and toe of high dam, the slope of dam face should not be flatter than 1:1 otherwise the toe or heel (specially the toe) may get sheared off. The procedure for design of theoretical profile of a high dam is as follows:

Let us assume that the dam is 140 feet high above river bed and that for particular values of \( \lambda \) and \( s \), the limiting height of low dam is 110 feet. This 140 feet dam for these values of \( \lambda \) and \( s \), is therefore a high dam. Taking the R.L. of top of dam as 140, the dam from R.L. 140 (truly speaking it should be from H.F.L.) to R.L. 30 will be designed as a low dam. From R.L. 30 to R.L. 0 (i.e. bed of river or the bottom of dam superstructure), it will be designed as high dam. The vertical depth of 30 feet from R.L. 30 to R.L. 0 will be divided into 10 feet thick strips or slices and first, the strip from R.L. 30 to R.L. 20 will be designed on the

![Theoretical profile of high gravity dam](Fig. 18(a))

principles of high dam. Next, the strip from R.L. 20 to R.L. 10 and finally, the strip from R.L. 10 to R.L. 0 will be designed on the same principles. This will give the theoretical
profile of a high gravity dam above the river bed. Usually the face slopes of dam superstructure near river bed are continued for some depth below the river bed. This portion of dam below river bed is called its *structural foundation*. The bed on which the bottom of structural foundation of dam rests, is called *foundation bed* or *natural foundation* of dam. Thus, we get the theoretical profile of dam above its foundation bed. In practice, this profile is slightly modified and then we get the *practical profile* of a high solid gravity dam. The theoretical and practical profiles of a high dam 140 feet above river bed are shown in figures 18(a) and 18(b) respectively.

![Practical profile of high gravity dam](image)

Fig. 18(b)

The procedure of designing a high dam in strips, as made out above, is a bit laborious and entails much loss of time. It is however an accurate method.

G. Molesworth has given simple formulae for the design of a high *stone masonry* dam and they are as follows (see fig. 19):

\[ x = \sqrt{\frac{0.05y^3}{\lambda + 0.03y}} \] feet, subject to a minimum of \( \frac{y}{\sqrt{s}} \)
(0.09y)^4 \text{ feet}

where, $x =$ downstream offset from vertical line (called axis of dam), at depth $y$ below H.F.L.

$z =$ upstream offset from axis of dam at the same depth below H.F.L.

$b_1 =$ value of $x$ when $y = \frac{1}{4}h$, $h$ being the depth of water upto H.F.L.

$a =$ the thickness of dam at H.F.L. and is equal to $0.4b_1$.

Theoretical profile of high gravity dam of stone masonry

Fig. 19

The dam portion beyond the limiting height of low dam may be designed in strips by using the formulae for $x$ and $z$; $x$ and $z$ will, in each case, be at the bottom of each strip so designed.

The stability of practical profile of low or high dam is usually checked analytically and graphically to see if the cross section provided will prove ample when the reservoir is empty and when the reservoir is full.

7. Uplift: Upward water pressure on the base of a structure is called uplift. In case of dam, it is the water pressure on base of structural foundation of the dam. The
uplift pressure comes into play only when natural foundation below the dam is not impervious and therefore, water seeps through natural foundation from upstream side to downstream side of dam. Maximum intensity of uplift pressure will be at the heel of dam and minimum at the toe of dam, as shown in fig. 20(a). The amount of uplift depends

![Diagram showing intensity of uplift pressure on base of dam](image)

Uplift on base of gravity dam

*Fig. 20(a)*

on the degree of permeability of natural foundation. Thus, if it is more permeable or pervious, the uplift will be more and vice versa. Uplift affects the stability and therefore the design of dam; hence it should be taken into account where it exists. There will be no uplift if a dam is founded on a sound ledge rock. The base of elementary profile of
a low dam, taking uplift into account, will be \( \frac{h}{\sqrt{s - c}} \) feet,

where, \( c \) is the coefficient of uplift and its value will be from zero to unity, more value being for more permeable or pervious foundation bed.

For sound ledge rock, \( c = 0 \) i.e. there is no uplift in such case.

For very permeable soils (e.g. alluvial soils), \( c = 1 \) i.e. there is full uplift.

For partly pervious and permeable foundation bed, \( c \) will be less than unity. Thus, if \( c = 0.4 \), we say that the uplift pressure is 40\% or the coefficient of uplift is 0.4.

From this it is clear that more base width of dam is necessary when there is uplift. To reduce the foundation uplift, a cutoff of necessary depth below dam base is provided at the heel of dam. This cutoff, which is usually in the form of a curtain wall, reduces seepage and therefore the uplift. To reduce the seepage further, a row of foundation holes at regular intervals along dam length may be drilled from the base of trench of curtain wall; these holes are filled with cement grout under pressure. As an alternative to cut-off, a few rows of holes are drilled through the foundation bed in the upstream one-third of bed and these holes are cement-grouted to produce some sort of impervious curtain through the foundation bed on upstream side. This process is called curtain grouting and is cheaper than curtain wall, though slightly inferior in utility. In addition to curtain wall or curtain grouting, a drainage gallery is provided in the upstream portion of body of dam and a few feet away from the upstream vertical face (i.e. axis) of the dam, as shown in fig. 20(b). A drainage gallery (i.e. foundation gallery) is a passage of certain cross-section area (usually 5' wide by 7\( \frac{1}{2} \) deep as seen in profile of dam) provided along the length of dam, with its base at 1.5 m to 3 m (5' to 10') above river bed and its upstream vertical side about 3 m to 4.5 m (10' to 15') from the axis of dam. A drainage gutter 30 cm \( \times \) 30 cm (12" \( \times \) 12") is provided in the base of gallery, near its upstream vertical side. From the base of this gutter, foundation drainage holes 20 cm to 30 cm (8" to 12") diameter and of required
depth are drilled. The water, seeping under pressure through the foundation bed, will rise up these holes into the drainage gutter; its pressure will thus get reduced sufficiently, resulting in the reduction of foundation uplift on the base of dam. The drainage water from the gutter is carried out of the body of dam by a few cross drainage galleries running at right angles to the foundation gallery which is also called the main or longitudinal drainage gallery.

![Diagram of a storage dam with a drainage gallery.](image)

**Storage dam with drainage gallery**

**Fig. 20(b)**

If the upstream face of dam is not watertight, water will seep through it and will exercise upward pressure on the portion of dam above the seeping water; also, there will be some leakage of water through the body of dam. To avoid this, the upstream face of dam should be highly watertight. In addition, a row of vertical drainage shafts or holes 12.5 cm to 8" diameter, at a certain distance centre to
centre along the length of dam, is left in the body of dam during construction. These holes have their bottom at the roof of foundation gallery and their top at or above H.F.L. If there is any seepage through the upstream face of dam, it will be intercepted by these holes and the seepage water will run down them into the drainage gutter of the main gallery from where it will be taken out of dam by the cross galleries.

Drainage gallery thus helps in draining the foundation bed and the body of dam.

8. **Conditions of stability of a solid gravity dam**:
A solid gravity dam should satisfy the following conditions in order to be stable and safe against failure:

(a) There should be no tension induced at any point on a horizontal plane (through the body of dam) at any level. Hence the lines of resultant force, when reservoir empty and reservoir full, should fall within the middle third zone of the profile of dam. This is shown in fig. 21. This fulfilment also ensures that the dam will not overturn about any point on the downstream face of the dam.

(b) Foundation bed should neither settle nor fail by shear under the load of dam.

(c) The masonry of dam should not get crushed. Hence, the maximum inclined compressive stress induced at any point on the upstream and downstream faces of dam (when reservoir is empty and when reservoir is full) should be less than the allowable compressive stress for the masonry of dam.

(d) A portion of dam should not slide on any horizontal plane at any level of dam. Hence, the horizontal component of the resultant water pressure on the portion likely to slide should be less than the weight of such portion multiplied by the coefficient of sliding friction between the base of this portion and the surface on which it may slide. The weight of this portion is inclusive of the weight of water on its upstream face if this face has a slope. Here, the shearing resistance of masonry of dam at the joints is neglected and this is on the safe side.
(e) The uplift, if any, should be considered because the uplift causes overturning moment on the dam.

(f) The cracks caused by temperature variations should not be serious; otherwise they will result in the leakage of water and the likely failure of dam.

(g) The induced shear stress, specially at the toe and heel of dam, should be less than the permissible shear stress for the masonry of dam.

![Diagram of lines of resultant force](image)

**Fig. 21**

While investigating the stability of dam, one running foot of dam at the deepest river bed (i.e., where the height of dam is maximum) is considered. In Metric system, one running metre of dam is considered for this purpose.

9. **Stresses in solid gravity dam:** The stresses induced in a solid gravity dam are *mainly* due to:
(a) Water pressure on the upstream face (i.e. back of dam).

(b) Weight of dam.

(c) Uplift, if any.

(d) Temperature variations.

Stress distribution on base of dam

Fig. 22(a).

The stress induced at any point in the body of dam due to all these causes should not be tensile; it should be compressive and that too within safe limit. The shear stress induced anywhere should also be safe. The distribution of vertical compressive stress due to (a) and (b) on the horizontal base of dam is shown in fig. 22(a) when the reservoir is full and when it is empty. The maximum vertical compressive stress is at toe and minimum at heel when reservoir is full; the maximum vertical compressive stress (of some other value) will be at heel and minimum at toe when reservoir is empty. The maximum inclined compressive stress will be at toe on a plane normal to the downstream slope at toe, when the reservoir is full; the maximum inclined compressive stress (of some other value) will be at heel on a plane normal to the upstream slope at heel, when reservoir is empty.