HYDROLOGY AND GROUND WATER

A PRACTICAL TEXT-BOOK FOR THE USE OF CIVIL ENGINEERS, SURVEYORS, STUDENTS, AND ALL THOSE WHO DEAL WITH THE CONTROL OF WATER

BY

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HYDROLOGY

AND GROUND WATER

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PREFACE

THE want of a comprehensive work on hydrology, ground water, and surface flow, has induced the author to compile this work in the hope that it will be useful to those engineers who are engaged in Water Works, Irrigation, and Drainage schemes.

Due acknowledgment has been given as far as possible to extracts and quotations from other sources. The author is indebted to the editor of "Engineering" for allowing articles which form the subject-matter of this book to be re-written and amplified.

J. M. L.

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CHAPTER I.

RAINFALL.

1. The source of all water, whether obtained direct from rivers or streams, or from storage reservoirs, or from ground storage by means of wells, is rain. A knowledge therefore of its character, seasons, and of the effects produced by it, is of primary importance to the civil engineer whose duty is to design, execute, improve, or maintain those works which are necessary for the control of water.

2. The circulation of the atmosphere is primarily caused by the air between the tropics, especially over the equator, being always heated by strong solar radiation, forming what may be called the great boiler of the motive power for the whole system of circulation. The heated air at the equator expands, rises through the surrounding air, and is carried as an upper current towards the poles, its place being taken and filled by other currents flowing at a lower level from the poles towards the equator. The masses of air thus carried in opposite directions polewards and towards the equator tend to balance each other at the Horse latitudes, about 30° north and south of the equator, causing areas of high pressure in these regions, which give rise to surface winds on the earth flowing from these areas of high pressure towards the poles, and towards the equator. The rotation of the earth affects the direction of these winds, causing the south-west winds towards the north polar regions; the north-east and south-east trades towards the equator, and the "Brave West" winds towards the south polar regions. The circulation of the air and resulting winds described above are affected by two causes, unequal heating of the air by land and sea surfaces, and the deflection of the prevailing winds by plateau edges, and mountain ranges. Regular zones of surface winds and climates consequently are found only in great expanses of ocean, and do not appear in narrow seas or on land. The great variation of temperature of the continents compared with the ocean modify and deflect these air currents in different parts of the world, producing the monsoons.

The atmosphere derives its moisture by evaporation from the surface of the ocean principally within the tropical regions; the humidity of the air being in proportion to the temperature, the quantity of rain which falls at any place, therefore, should be in proportion to the temperature of the air at the place, and this, as a general rule, is true. In intertropical regions the equatorial belt of low pressure always lies nearly under the vertical sun, consequently, in the northern summer, it swings to the north, and in the southern summer it swings to the south. All parts of the earth's surface that this equatorial belt traverses in its annual movement experience a rainy season as it lies over them, and a dry season all the rest of the year. Near the equator, where the belt of low pressure crosses a tract of the earth, both in its northward and its southward swing there are two wet and two dry seasons in the year. This belt of rain moves northwards and southwards through a range of 5° annually, and is known as the equatorial rain belt, being in the centre of a larger belt, called the equatorial cloud belt.

The form of the land and the prevailing direction of the wind at any place with reference to sea or land also alter the conditions of the problem, so that the amount of rain varies considerably in different parts of the world, and is dependent on the direction of the moisture-laden sea winds. In all places not reached by these winds, or wherever high ranges of mountains cut off the rain-bearing winds, the rainfall is slight. Even on the coast where the prevailing wind is off shore there may be scarcely any rain, as on the west coast of tropical South America, while in the very heart of a continent the rainfall may be heavy where the sea wind blows across a great plain before striking the mountains, as in the eastern slope of the Andes. An attentive study of a rainfall map of the world with those of wind and configuration of land surface will show reasons for the local distribution of rainfall in all parts of the world.

3. In the dynamic theory of the formation of clouds, rain, hail, and snow, the work done by the expansion of air under pressure, is done at the expense of the heat contained in the air and the vapour, and soon reduces the temperature of the vapour to its dew-point. The further cooling and consequent condensation give rise to an evolution of the latent heat of vapour, so that the process of cooling is retarded as the rate of condensation is increased. The total quantity of heat represented by falling rain, hail, or snow is left in the cloud, and promotes further rise and overflow, but is eventually lost by radiation. So long as the cloud, or air, retains this excess heat, it is more buoyant

than the neighbouring air, and promotes the formation of winds and storms.

Rain is caused in practically every instance by moist air being thermodynamically cooled by expansion brought about by its ascent from lower to higher levels. Anything which will cause the ascent of large volumes of moist air will, if sufficiently persistent, result in precipitation. Mountain ranges in any country considerably affect the distribution of rainfall, resulting from the condensation of aqueous vapour due to the cooling of masses of moist air driven up a mountain slope by the prevailing winds; the region of maximum precipitation being at the lower cloud limit on the windward slope of the range; and above this height the latent heat liberated by condensation raises the temperature above the dew-point, resulting in a decreased rainfall. After crossing the summit of a high range the descending mass of air contracts in volume, thereby raising the temperature rapidly above dew-point, resulting in a marked decrease of precipitation. The south-west or summer monsoon of India affords an example of the effects of mountain ranges on the distribution of rainfall. The "south-west" winds are a relatively small part of a general circulation of the atmosphere caused by a region of high pressure over the South Indian Ocean and a region of low pressure which extends over the whole of Central Asia. Air passes northwards from the region of high pressure as the south-east trade winds as far as the equator, where it gets caught up in the circulation around the low pressure over Asia. On account of the particular arrangement of sea and land, combined with deflection of wind currents due to the earth's rotation, this air travels for 4000 miles over the sea before it reaches India, where it arrives as a warm and humid wind. This warm and moist air would probably sweep right across India towards Central Asia without producing much rainfall, if it were not for the distribution of mountains round India. From the north of the Mekran coast right round the north of India, following the line of Afghanistan, the Himalayas, and the mountains of Burmah, there extends an unbroken wall nowhere lower than 5000 feet directly athwart the air currents already described. These mountain ranges catch the air which is being driven by a pressure distribution extending from the Southern Indian Ocean to the centre of Asia in a kind of trap, out of which there is no escape except by ascension. The damp humid air which begins to rain as soon as it rises 500 feet is forced to rise between 10,000 feet and 20,000 feet. In consequence, large masses of water are precipitated over the greater part of India;

a comparatively small amount is deposited on the tableland of Thibet, and practically no rain reaches the Gobi.

The amount of rainfall generally increases as we ascend the slope of a mountain up to a certain limit. It has been calculated that half the vapour in the atmosphere is contained in the lowest 6000 feet, and that at a height of 20,000 feet there is only one-tenth of the moisture that exists at the surface of the earth ; the point of maximum rainfall on a mountain slope depends, therefore, on the mean height of the plane of condensation or mean cloud level, which may be ascertained from the prevailing meteorological conditions obtaining at a locality. In India the elevation of the line of maximum rainfall appears to be about 4500 feet above sea-level. In the British Isles the height of maximum rainfall in Cumberland is about 2000 feet above sea-level. In summer the altitude at which clouds float is greater than it is in winter, and they float at a greater height in warm than in cold climates.

The slope of the hills, however, influence the height of maximum rainfall; a very precipitous elevation may result in a decrease of rainfall. A rain cloud as it rises expands and cools, tending to precipitation, but where the windward sides of the mountain slopes are steep, until the clouds rise above these slopes there is a tendency to compression, which may reduce or prevent precipitation until the crest is reached, when a sudden fall of pressure occurs. In high mountain regions the rain clouds become entangled among the ridges, and part with a greater portion of their moisture, becoming thus exhausted before the summit is reached; but in ranges of moderate height when the windward slope is steep, precipitation is prevented or retarded until the summit is reached, and the leeward side of the range may receive more rain than the windward slope. As an example, the mountain range of the Western Ghats of Peninsula India, which run parallel to and from 30 to 60 miles from the Bombay coast, rise precipitously from the coastal plains to a height of from 2000 to 3000 feet above sea-level; the steep hill-sides of the windward or sea face of the range are comparatively bare of trees and scrub, and receive but a small portion of the south-west monsoon rains, while at the crest the rainfall is great, and continues heavy down the lee slopes, the intensity diminishing as the monsoon proceeds inland.

4. We thus see that a continual circulation of water takes place between the hydrosphere and the atmosphere. Sea winds carry water vapour against the land, and ascending currents raise it high into the atmosphere, where it condenses and returns

as rain, and is carried back by springs and rivers to the sea. In all regions not reached by sea winds, the rainfall is very slight, and evaporation predominates. Such regions occur in every continent wherever the arrangement of the heights cuts off rainfall, where there are no rivers, or where rivers flow into dwindling salt lakes; that is, nearly rainless regions of internal drainage.

5. Rainfall is represented on maps by lines of equal precipitation termed Isohyets. These represent actual figures without reduction for elevation or other local conditions, so that a rainfall map can be studied as a direct record of actual facts. The rainfall maps for the separate months show the intimate relation between rainfall and the direction of wind, taken in conjunction with the configuration of land. The rainfall map of a hydrographical basin is made by establishing rain-gauges in the basin, and along its water-shed at points likely to give the fairest mean of the fall on separate areas. The result of the rain-gauge readings should be collated with observations of gauges in the vicinity outside the boundaries of the basin, and from them isohyetal lines drawn, by means of which a fair estimate of the rainfall over the basin can be estimated.

6. The practical value of exact statistics of rainfall is greater than that of any other climatological condition, for the water supply and fertility of the land depend in every case on the rain that falls either locally or on the heights of the water-sheds. The Atlas of American Agriculture marks an important advance in the accurate charting, and discussing of many of the essential features of the climatic conditions of that large area; and the same may be said of the Australian Commonwealth Bureau of Meteorology.

CHAPTER II.

MEASUREMENT OF RAINFALL.

7. The amount of rainfall in any given shower at any locality is measured by the depth of the pool of water in inches which would be formed if the ground were perfectly horizontal and none of it soaked in, or evaporated, or flowed away. The instrument employed for determining the amount of rainfall is called a rain-gauge. On emergency a rain-gauge can be made out of a biscuit tin, or any vessel with vertical sides, and an unobstructed mouth. Such a vessel standing level would collect the rain, the depth of which could be measured by an ordinary inch rule. It is rare to find rain so heavy as to give any appreciable depth, and in order to estimate the amount of rainfall to small fractions of an inch, the device is employed of measuring the water collected in the receiver of the gauge in a glass tube of smaller diameter than the mouth of the collecting funnel. Thus, if the funnel exposes an area of 50 square inches, and the measuring glass has a cross-sectional area of 1 square inch, the fall of one-fiftieth of an inch of rain on the funnel of the receiver will give a quantity of water sufficient to fill the measuring glass to a depth of 1 inch. The smallest diameter for a serviceable rain-gauge is 5 inches, and is the size generally used. Trials with gauges of various diameters ranging from 1 inch to 2 feet have shown that if they are set perfectly level, and observed with great care, exactly the same rainfall has been registered by them all. In order to get good and trustworthy observations, it is necessary to have good instruments and conscientious observers.

8. *Rain-gauges.*—The Snowdon pattern rain-gauge, which is generally used in this country, consists of a metal cylinder, the top of which is an accurately turned brass ring 5 inches in diameter, set perfectly level. The rain which passes through this ring is conducted into a glass bottle, which is enclosed in the lower part of the rain-gauge. The lower part of this gauge is sunk into the ground so that the temperature changes little. The amount of water is measured daily by pouring the contents of the bottle into a tall narrow glass graduated on the side into

divisions, each of which represents one-hundredth of an inch of rain on the ground. In the British Isles, for the sake of uniformity, and for reasons given below, the rim of the gauge is placed 1 foot above the surface of the ground. Experience has shown that the higher the gauge is above ground level the smaller is the quantity of rain caught, owing to the eddies caused by the wind about any prominent upstanding object. It is therefore of greater importance to have rain-gauges placed at a uniform height above ground level, than to have them of uniform diameter. One foot above ground level is now recognised as the standard height. The following table, based on Beadmore's "Hydrology," shows the multiples to be used for increasing the quantity of rain observed at any height above ground level, so as to make the observation equal to that at ground level.

Height of Gauge above Ground Level.	Multiplier.	Height of Gauge above Ground Level.	Multiplier.	Height of Gauge above Ground Level.	Multiplier.
5 feet.	1·036	25 feet.	1·164	45 feet.	1·267
10 ,,	1·070	30 ,,	1·192	50 ,,	1·294
15 ,,	1·104	35 ,,	1·220	—	—
20 ,,	1·134	40 ,,	1·242	—	—

The meteorological department of India use a Symon's rain-gauge, the funnel being provided with a brass rim, which should be truly circular and exactly 5 inches in diameter; and the gauge is fixed with its rim exactly 1 foot above ground level.

Rain-gauges should be set in open situations away from trees, walls, and buildings; at the very least as many feet from their base as they are in height; and should be so firmly fixed that they cannot be blown over. The gauge is either planted in the earth and fixed by stakes or placed in a hole, which exactly fits the gauge, in a block of concrete. The top of the rim should be 1 foot above ground-level at the site of the gauge, and the rim must be truly level. Rain-gauges in this country are read at 9 A.M. mean civil time of the locality, and record the rainfall of the past twenty-four hours. It cannot be too strongly impressed on observers that they must be strictly punctual to the hours of observation.

All original observations should be written down at the time they are made in a properly ruled or printed note-book (not on loose slips of paper), so that they may be available for reference in case any question should arise about them afterwards. Omissions must be carefully avoided, otherwise true means cannot be obtained. It is therefore necessary to have a well-trained deputy to take the observations in the absence of the usual observer. In entering the observations in the register, it is absolutely essential that they be correctly copied from the original note-book, and the entries should be checked by reading against the originals. It is desirable that very heavy falls of rain should be measured immediately after their occurrence; the duration of the fall should be noted also at the same time; but care must be taken that the amount is included in the next ordinary registration. Details of all known heavy falls of rain on a hydrographical basin, their duration, and the circumstances under which they may be expected, are important records, and should be carefully maintained. It is a well-known fact that during any heavy and continuous fall of rain lasting a few hours a much larger proportion of it flows off from the ground, than if the same amount of rain had been spread over a longer period, and hence the great floods to which all countries are subject.

No change should be made in the position of a rain-gauge, as a change might introduce an alteration in the amount of rain measured, and a comparison with previous records would be misleading.

When snow falls, that which is collected in the funnel of the gauge is melted and measured. If the snow has drifted, or if the funnel of the rain-gauge cannot hold all that is fallen, a section of the snow should be obtained in several places where it has not drifted by inverting the funnel of the rain-gauge, turning it round, lifting and melting what is enclosed. The section should, if possible, be taken from the surface of a flat stone. Care must be taken that the section is of snow that has fallen during the 24 hours, and does not include any previously fallen snow. It is also desirable to measure with a foot rule the depth of snow in several places where it has not drifted, and enter the observation in the "Remarks" column of the register. A fall of 13 inches thickness of undrifted snow is equivalent to a fall of 1 inch of rain, but the proportion varies considerably in different falls.

There are several patterns of self-recording rain-gauges. The two principal types are the float pattern, and the tipping-bucket pattern. In the former the rain is collected in a reservoir in which there is a float carrying a pen, and as the float rises a trace is marked on a moving chart showing the rate at which the rain fell. In the tipping-bucket pattern the rain is collected in a small tilting bucket, divided into two equal parts, which tip over alternately when 0·01 inch has fallen; a lever carrying a pen is then raised by means of an escarpment wheel, and a trace resembling a series of steps is recorded on the chart. A check on self-registering gauges, which are read weekly or monthly, is to compare the results furnished by them with the daily records of the nearest available rain-gauges.

Rainfall registers are important records, and should be abstracted and the original records carefully preserved.

Additional Observations.—On the occurrence of any exceptional phenomena such as floods, whirlwinds, showers of dust, damage by lightning, hail, etc., steps should be taken at once to gather accurate information respecting such occurrence, which should be carefully entered in a register. In the case of floods, an effort should be made to have a permanent mark cut in a wall, or on the piers of a bridge, recording the height and the date of the flood. Observations on the depth of water in wells afford very valuable information as to the quantity of water which has passed into the ground from time to time, and is there stored for future use. It is desirable that for such observations the well selected should be as remote as possible from other wells, especially those which are being constantly pumped from. The measurement should be made from a fixed point at the mouth of the well to the water surface, as owing to the common practice of deepening wells in times of drought, errors are likely to arise if the depth of water in the well only is measured. The water surface should be referred to the Ordnance, or any other fixed datum. Such measurements should be taken at least once a week, but in the beginning of the rainy season of the year more frequent observations will be found necessary to determine the lowest level to which the ground water plane of saturation sinks, and the exact period when this level begins to rise. The well or wells selected for observations should be some distance from a river or a stream, so as to be out of their influence. On account of the difference in the fluctuation in various wells in the same district, observations in any well can be compared only with the same well, and not with observations in other wells in the district, unless all the conditions with reference to the ground water of the district are known, and the differences in the fluctuations between various wells have been carefully compared.

Rainfall statistics should show :—

(1) Mean, maximum, and minimum monthly rainfalls.

(2) Mean, maximum, daily falls in twenty-four hours.

(3) Special occurrences, such as the hourly rate of fall of heavy rainfall ; longest continuous falls ; droughts.

9. In the case of irrigation schemes, or projects for a water

supply, it is always desirable that the rainfall on the hydrographical basin should be ascertained as far as possible by direct observation on the ground itself; and the selection of sites for establishing rain-gauges should receive careful consideration. Unqualified reliance on a single gauge in the basin may cause serious errors in estimating the yield that may be expected from the basin. The very small area of a single gauge is also subject to much greater variations in shorter periods than can possibly occur over large areas. For basins of some magnitude, two rain-gauges for every 1000 acres are required; on smaller areas the proportion necessary for equal accuracy must be greater. A single rain-gauge will be subject to greater perturbations than can occur when the mean of several gauges near together are considered; hence isolated gauges occasionally show greater deviations in particular years from the true mean. Sir John Benton, sometime Inspector-General of Irrigation in India, considered the least number of rain-gauge stations inside the boundaries of a hydrographic basin which would afford a reasonable safe estimate of the rainfall on the basin to be:—

Area in square miles,			0 to 50.	Least number of rain-gauge stations,			1.
,,	,,	,,	50 ,, 100.	,,	,,	,,	2.
,,	,,	,,	100 ,, 200.	,,	,,	,,	3.
,,	,,	,,	200 ,, 350.	,,	,,	,,	4.
,,	,,	,,	350 ,, 500.	,,	,,	,,	5.
,,	,,	,,	500 ,, 700.	,,	,,	,,	6.

For a single mountain valley, Dr. Deacon suggests five rain-gauge stations, three in the axis of the valley, of which one is near the junction of that axis with the boundary of the watershed; and one rain-gauge on each slope about the middle height, and approximately in a line perpendicular to the axis of the valley passing through the centre gauge. Each gauge should have 10 to 15 yards around it of an uninterrupted plain representing the general level or inclination of the ground for a much larger distance beyond. The arithmetical mean of the four gauges, which may be checked by the central gauge, will give the mean rainfall on the area ("Encyclopædia Britannica," "Water Supply").

Dr. Mill states that the only way by which a fair estimate of the total rainfall on a hydrographical basin can be obtained is by constructing a map showing the physical features of the area, and the surrounding country, and also showing not only the readings of the rain-gauges within the basin under consideration, but also those at all available surrounding stations to a distance of many miles. He considered that while there were undoubtedly local variations of average rainfalls, these were all in harmony with the general principles of the relation of rainfall to the land and prevailing winds, and knowledge of the general distribution of rainfall over a wide stretch of country was an immense help in deciding on that of any small area within it. The stations outside the area would often prove of the utmost service in outlining the zones of rainfall on the map ("Proc. Inst. of Civil Engineers," Vol. CXCIV.).

CHAPTER III.

VARIATIONS OF RAINFALL IN A LOCALITY. CYCLE OF RAINFALL.

10. Among all phenomena of nature, rainfall is the most variable. In some cases the variation is very considerable, the maximum annual rainfall being very much in excess of the minimum, but the worst feature of the variation is, that there will sometimes occur several consecutive dry years. At places where the average rainfall is large, the extremes of both wetness and dryness will be less pronounced than at those where the usual rainfall is small.

The rainfall of a country or locality is generally assumed to be the mean annual rainfall observed over a period which is sufficiently long to produce a fairly constant mean value. It is necessary that the observations should extend over a long period of time owing to the wide range of the irregular variations, and the rare occurrence of the extreme values. The mean rainfall is the most probable value of the yearly fall, and is a real characteristic of the rainfall of a country or locality.

11. In the study of the rainfall of a country or a locality it is necessary to consider not only the amount of the rainfall, but the deviations from the mean annual rainfall, and the maximum deviations $\pm$ that may be expected from the mean. Thirty to thirty-five years is the shortest time that may be profitably considered in arriving at a mean value for the annual rainfall of a locality. The mean of fifty to sixty years' observations would give substantially better results. The most convenient method of deducing the true mean annual rainfall of a locality would be to assume the mean of thirty-five years' rainfall or multiple of thirty-five years, as the mean rainfall of the locality. Sir Alexander Binnie considered the true mean to lie somewhere between thirty-three and thirty-five years. From rainfall records taken from twenty-six stations scattered over the world, he arrived at the following deviations from the mean of fifty-three years for shorter periods :—

Year Means.	5	10	15	20	25	30	35
Mean deviation per cent.	14·93	8·22	4·77	3·27	2·75	2·26	1·79
Maximum ,, ,,	29·6	16·1	12·5	9·2	9	6·9	6·7
Minimum ,, ,,	6·8	1·0	0	0	0	0	0

From fourteen stations scattered over the world he arrived at the following conclusions:—

The percentage of years in which the rainfall is above the mean is 45·8.

The percentage of years in which the rainfall is below the mean is 54·2.

The mean fall of the "wet years" is 1·19 of the mean rainfall.

The mean fall of the dry years is 0·83 of the mean rainfall.

The maximum annual rainfall is 1·52 of the mean.

The minimum annual rainfall is 0·59 of the mean.

The mean fall of the three consecutive driest years is 0·76 of the mean.

The proportional number of periods of three consecutive dry years was 20·3 in 100 years ("Proc. Inst. Civil Engineers," Vol. XXXIX.). Sir Alexander considered that there is some force at work in nature of which nothing is known, but which keeps the deviation of rainfall from the mean within certain clearly marked limits, and that the study of rainfall is not to be regarded as a local circumstance or a matter of a few inches, but as a great natural phenomenon. Sir Alexander's conclusions regarding the ratios of the maximum and the minimum annual rainfalls to the mean rainfall of a locality cannot be accepted as applying to all regions of this world, but indicate the manner in which the rainfall of a locality should be analysed. The degree in which the rainfall of any given year is likely to deviate from the mean is proportionally greatest in the driest part of a country. That is the more copious the rainfall of any tract is, the less the variations are there from the mean.

Dr. Deacon considers that a total rainfall during any period of fifty years will be within 1 to 2 per cent. of the total rainfall at the same place during any other period of fifty years, and a record of twenty-five years will fall within 3½ per cent. of the mean of fifty years. He also considers that for a period of fifty years there is nearly a constant ratio on any given area, exceeding about 1000 acres, between the true mean annual rainfall, the rainfall of the driest year, the two consecutive driest years, and any other group of consecutive driest years. Thus in any period of fifty years the driest year on any given area, not at an individual gauge, will be 63 per cent. of the mean rainfall of the fifty years. That in the two consecutive driest years the rainfall will be 75 per cent. of the mean. In the three consecutive driest years 80 per cent. of the mean. The four consecutive driest years, 83 per cent. of the mean. The five consecutive driest years, 85 per cent., and the six consecutive driest years, about 86½ per cent. of the mean ("Encyclopædia Britannica").

12. The mean rainfall over a long period can be determined for an area upon which the actual fall is recorded for a comparatively few number of years, by assigning to the missing years of the short-period gauges, rainfall bearing the same proportion to those of corresponding years in rain-gauges with records extending over a long period, that the rainfall of the known years in the short-period gauges bear to those of corresponding years in the long-period gauges. It is always advisable to select as standard, long-period gauges so situated that the short-period gauges lie between them. Thus if—

a represents the mean rainfall of the standard gauge for a short period of s' years.

A represents the mean rainfall of the same station for a long period of n years.

b represents the mean rainfall of the station with a short period of s' years.

B, the corrected mean rainfall of the short register station

$$B = \frac{bA}{a}.$$

Provided the rain-producing conditions are the same for the two stations.

As an example in early days before rain-gauge stations were established over India, Sir Alexander Binnie, in the case of the Nagpur waterworks, found the mean monsoon rainfall at Nagpur for the four years, 1869 to 1872, to be 39·5 inches. At that time the only stations with any long period of records were Bombay, Calcutta, and Madras. The Madras records were not suitable, as it received the greater part of its rainfall during the north-east monsoon, which does not usually appear as a rain-bearing wind at Nagpur. At Bombay, situated 500 miles to the south-west of Nagpur, he had a station with a long-period record, and which, like Nagpur, derives nearly all its rainfall from the south-west monsoon. The mean monsoon rainfall at Bombay for the four years, 1869 to 1872, was 82·8 inches, while the mean monsoon rainfall for a period of fifty-six years was 76·80 inches, from which Sir Alexander deduced the mean monsoon rainfall at Nagpur to be $39{\cdot}5 \times \frac{76{\cdot}80}{82{\cdot}80} = 36{\cdot}66$ inches.

Deviations from this rule are most likely to occur in localities with a dry continental climate, or which lie geographically between localities of marked lower and higher rainfall, as a slight deflection of the rain-bearing winds would produce a considerable difference in the absolute rainfall.

13. *Cycles.*—Mr. Thomas William Keele, from observations of rainfall in Australia, the British Isles, and from records maintained in Egypt of the Nile floods from A.D. 640 to A.D. 1451, considers that the period of a weather cycle is seventy-six years (" Proc. Inst. Civil Engineers," Vol. CCII.). The Hindus have a cycle of sixty years, the result, probably, of centuries of observation, each year bearing a name which indicates, among other events as likely to happen, the nature of the agricultural season, and so indirectly the rainfall of the year. It is interesting to note that the year 1878, stated by Blandford to be the year of the greatest excess of rainfall for the whole of India over the mean for the twenty-two years preceding 1889, corresponds to the year " Bohu Dhaniya," or year of abundance of grain in the Hindu cycle. The statement below shows the years of maximum and minimum rainfall in India as a whole—years of maximum rainfall, 1878 and 1917 (highest on record), difference, thirty-nine years ; years of minimum rainfall, 1877 and 1918, difference, forty-one years. Endeavours have also been made in California to trace evidence of climatic fluctuations by tree rings.

The British Isles occupy a position in the region of maximum rainfall of the north temperate zone, which makes the study of their rainfall difficult. The extremely wet year of 1872 was the greatest in the nineteenth century, and equalled that of 1903 all over the British Isles. The year 1872 seemed to be a remarkably wet year, not only in England, but over a greater number of stations in Europe, and possibly further south. In 1921 the rainfall was least in England and Wales since 1788. The previous great drought was in 1864. The other dry years were 1854 and 1887. The conditions which commonly prevail in the British Isles during dry spells are : High pressure over the British Isles, the greatest deviation from normal being usually over South-East England. Low pressure over the Arctic regions, especially near Spitzbergen, and generally low pressure over the tropics. The high pressure over the British Isles is reckoned to be related to the eleven-year sun spot cycle, occurring most frequently two years after sun spot minimum, and three or four years after sun spot maximum, so that it tends to recur every five or six years. Low pressure over the Arctic is related to ice conditions, and tends also to recur every five or six years. Great droughts only occur when both these factors are favourable. With pressure low over the Arctic regions, two or three months' warning of a drought would be given by the development of high pressure over Northern Russia.

Sun Spots.—The real nature of sun spots is still disputed, but there is little doubt that they are something of the nature of whirlpools or storms in the sun's photo-sphere. It has been discovered by long series of observation that the number of sun spots visible on the surface of the sun varies through a period of eleven years. The last maximum period was in 1917, and the minimum period was in 1923. On 1st February, 1923, an examination of the sun showed one small sun spot. No eleven-year recurrence of weather attributable to the sun spots has been found at Greenwich. In some countries there is a hotter climate than usual during the maximum sun spot period, while in other places the weather is cooler. Mr. G. T. Walker found the correlation between sun spots and rainfall too small to be significant, and that from forty years' observation as a whole the temperature of the earth was lower at the times of sun spot maxima than at the times of sun spot minima. There is little doubt that sun spots have some influence on terrestrial meteorology, because the development of a large sun spot is invariably accompanied by electrical disturbances on the earth, but we cannot yet go further than stating that the appearance of a large number of sun spots on the sun's photo-sphere indicates that the sun is in a condition of abnormal activity.

That there are certain fluctuations in the value of climatic elements is an established fact, and the so-called Brückner period, averaging thirty-five years, is generally recognised. No definite or universally accepted conclusion has yet been reached regarding the existence of other longer cycle periods.

CHAPTER IV.

YIELD FROM RAINFALL; EVAPORATION; TRANSPIRATION; PERCOLATION.

14. Of the rain that falls upon the earth, a portion returns to the atmosphere; a portion percolates into the soil, and reappears as vegetation, or is evaporated from the soil, or remains as ground water; another portion remains on the surface, and forms streams, rivers, ponds, and lakes. A knowledge of the phenomena that pertain to these changes in condition, and of the physical and chemical properties of the water itself constitutes the science of hydrology. Every feature of this science is of direct value in the economic development of a country. Temperature affects evaporation and rainfall, and thereby affects the yield of a hydrographic basin. Low temperatures exert a further effect, mainly on the distribution of flow by forming ice and snow, and temporarily storing the precipitated moisture. The geological character of a basin also affects the yield; large areas and a great depth of sand, where if the rainfall is copious, while reducing the amount of surface flow, form the best natural reservoirs of ground water. On the other hand, if the basin consists of bare impervious and unfissured rock, it is evident that the whole rainfall discharged on it less the amount evaporated, will flow off the ground and thus be lost unless collected and stored. Where the basin is wooded or covered with forest and undergrowth the rainfall is retained and allowed to pass off slowly. This protection against evaporation makes forests and woods the guardians of streams. The uneven forest floor and its sponge-like qualities stop the rapid and ruinous draining of surfaces with its attendant denudation, and favours slow percolation into the soil, thus producing a steady supply to springs.

15. The yield of, or the supply of, water that may be expected from a hydrographical basin, either from direct flow, or from water that has percolated to, and reached the ground-water plane of saturation is affected by its configuration, geological structure, condition of climate, nature of vegetation, and in the case of surface flow by the intensity of the rainfall. The subject

is complicated by other varying influences, so that each basin must be dealt with on the data available. All methods of computing rainfall and other physical data should be used for the purpose of analysing, supplementing, and extending observed records.

The run off or surface yield from a hydrographical basin is that portion of the rainfall which remains on or near the surface of the ground too short a time to be taken up or lost by evaporation. A varying portion of this is underground flow, but that which is sub-soil flow in one place may appear as surface flow in another. As the slow movement of ground water tends to equalise the seasonal variations of rainfall, the ground flow is fairly constant for any basin, and largely governs the low water flow of the stream draining it. The flood flow or freshets are governed by the irregular manner in which the rain falls on the basin.

Of the water that percolates into the earth after rainfall, a part is re-evaporated, a part is transpired by vegetation, a part comes to the surface and escapes as surface flow, and the remainder percolates downwards into the soil until it is held up by impervious strata, or reaches the ground-water plane, below which every pore space of the soil, every crevice, hollow, and fissure in the earth's crust is filled with water, and the escape, laterally, of the ground water equals the addition from percolation. The lowest level of escape is generally the level of the sea, below that level the rocks and soil are saturated. The depth of percolation of ground water into the earth is not known; it may reach even as far as the intensely-heated interior of the earth, as capillary water has the capacity of penetrating rocks even against high counter-pressure of vapour. Within the earth the ground water is in constant circulation through the pore spaces of rocks, through fissures, and through channels along joints, evincing its power as a geological agent by its chemical and mechanical actions.

The amount of supply to ground water is dependent on the rainfall, and the laws which govern the flow of water through soil, which may be by gravitation or capillary action. There are other factors also which influence its flow, the passage of a low barometric depression across a section of the country is always associated with a more rapid discharge of water from springs, flowing wells, and seepage outlets; the eruptions of volcanos are often preceded by a failure or diminution of the supply from wells and springs in the district; the rate of seepage is modified by changes in soil temperature; the settling of silt and fine sediment over coarse beds as consolidation takes place, partly by compression and partly by accumulation of sediment, causes the water contained in the coarser beds to be expelled upwards, downwards, or laterally. The supply to ground water is practically that due to percolation from rainfall, seepage from streams and rivers, and seepage from pools, lakes, and standing water. The yield, therefore, of a hydrographical basin, including surface flow and ground flow, will be the rainfall on the basin less losses, and these losses are—

(*a*) Evaporation from water surfaces in the basin;

(*b*) Evaporation from the soil;

(*c*) Transpiration by vegetation according to the seasons, temperature, and nature of the vegetation.

Were it not for these losses, the volume of streams flowing into the sea would be greatly increased.

16. The power of air to carry off moisture is very considerable, the Mediterranean Sea affords an example of the considerable amount of evaporation from water surfaces, for notwithstanding the rivers flowing into it, the accession to its waters does not keep pace with the evaporation from its surface, as except for an occasional outward current, there is almost a constant inset of current into it, through the Dardanelles, and the Straits of Gibraltar. In the case of a liquid exposed to air and at atmospheric temperature, the rapidity of evaporation increases with the extent of the surface of water exposed, the dryness of air, and the rapidity of renewal of the air immediately above the water surface. Evaporation from large surfaces of water are less than from small pans or evaporometers, owing to the greater humidity over the surface of large bodies of water. It has been ascertained by Mr. Palmer from elaborate records of evaporation maintained at Rajputana, India, that if the evaporation from a tank not more than 4 feet in depth, as an average, be taken as unity or 1, then that from an evaporometer in a low and somewhat sheltered locality was 1·15, and from an evaporometer in an open and wind-swept spot, 1·41. Had the tank been deeper, the ratio would have been still more in its favour ("Proc. Inst. Civil Engineers," Vol. CXCIV.).

The statement below shows the evaporation from a circular pan, 3 feet in diameter, floating in the Red Hill Reservoir, situated 8 miles from Madras. The mean temperature and relative humidity are those observed at Madras, the climatic conditions at Red Hills are probably drier.

1. Month.	2. Evaporation from Water in Inches.	3. Mean Temperature at Madras. Degrees F.	4. Relative Humidity at Madras. Per Cent.	5. Rainfall at Red Hills. Inches.	6. Remarks.
1914. October .	2·35	80·4	84	22·06	Evaporation for 17 days.
„ November	3·4	78·4	82	8·51	Evaporation for 22 days.
„ December	4·0	77·1	76	0·31	Evaporation for 27 days
1915. January .	3·37	76·3	80	5·96	——
„ February	4·35	78·5	77	0·53	——
„ March .	6·30	81·8	77	0·00	——
„ April .	7·60	84·7	76	0·06	——
„ May .	9·00	89·6	65	0·21	——
„ June .	6·60	88·2	67	1·45	——
„ July .	5·85	84·7	74	7·78	——
„ August .	7·35	85·4	72	1·76	——
„ September	8·05	83·8	76	3·31	——
„ October .	2·30[1]	83·5	78	2·64	[1] Evaporation from *1st to 10th October.*
„ November	—[2]	79·1	85	19·55	[2] No record; instrument out of order.
„ December	1·4[3]	76·3	74	1·02	[3] Evaporation 22nd to 31st December (10 days)

Note.—Col. 3 shows mean temperature in the shade.

Assuming the evaporation constant for the month we get—

1914.	October.	Evaporation,	4·28 inches.
„	November	„	4·64 „
„	December	„	4·60 „
1915.	October	„	6·5 „
„	November	„	no record.
„	December	„	4·34 inches.

Assuming the evaporation in November, 1915, equal to that of November, 1914, we get for the year 1915 at the Red Hills :—

Evaporation from surface of reservoir, 73·955 inches.
Rainfall at site of reservoir, 43·88 inches.
Mean temperature in the shade at Madras, 82·66° F.
Mean relative humidity at Madras, 75·1 per cent.

Evaporation records in Egypt show for a mean temperature dry bulb 90·50° F. in the shade; per cent. of humidity, 20; rainfall, nil; mean evaporation, 1·32 feet per month. In the

British Isles, careful observations at the Staines Reservoir, Thames Valley, gave the following results :—

Year.	Mean Temperature in the Shade.	Mean Relative Humidity, Per Cent.	Evaporation from Water, Inches.	Remarks.
1903 .	48·5° F.	79·1	26·3	Relative humidity that recorded.
1904 .	47·6° „	79·4	22·8	at Greenwich.

The maximum monthly evaporation : 4·4 inches in August, 1904. Maximum daily evaporation: 0·6 inches in 1904, and 0·48 inches in 1903.

At Glencorse from an iron tank 6 feet square and sunk 2 feet in the ground and within 3 inches of the rim of the tank, read daily at noon by means of a hook gauge, showed a mean annual evaporation of 12 to 13 inches for the years 1862 to 1904. The minimum being 9·10 inches in 1866. Rainfall, 37·50; and the maximum, 27·90 inches, in 1895. Rainfall, 39·80. The mean annual rainfall for the period 1862 to 1904 being 38 inches. The evaporation gauge is situated at a level of 900 to 1000 feet above sea level. The mean annual temperature, and the mean relative humidity at Edinburgh for the period 1862 to 1904 being 47° F. and 83 per cent. ("Proc. Inst. Civil Engineers," Vol. CLXVII.). Dr. Mill states that the various comparisons made annually in "British Rainfall" between the evaporation from a 6-foot square tank at Camden Square, and the meteorological elements showed that evaporation from a water surface bore a very close relation to the mean temperature of the air in winter, when, however, very little evaporation occurred, and to the duration of sunshine in summer. The influence of wind, though greater in winter than in summer, had been shown to be comparatively unimportant. It was also difficult to ensure that the conditions of different evaporation gauges were perfectly comparable ("Proc. Inst. Civil Engineers," Vol. CXCIV.). Dr. Walter Leather gives the following formula for calculating the evaporation from a free water surface :—

E = evaporation in millimetres for twenty-four hours.
D = dryness = 100 − humidity at 8 A.M.
w = mean wind velocity for the twenty-four hours in miles per hour.
T = mean temperature in shade in degrees F. for the twenty-four hours.

$$E = 2{\cdot}00(\log T - 1{\cdot}74) + 0{\cdot}33(\log D - 1{\cdot}00) + 0{\cdot}36(\log w - 0{\cdot}125).$$

Where a water surface is protected or covered in, the loss from evaporation is considerably reduced. At Menzies, Western Australia, observations in 1910 showed the annual evaporation from an exposed water surface to be 151·93 inches, while from a covered tank it amounted to only 2½ inches.

17. Except in arid regions, the mantle of soil sand, gravel, and clay which nearly everywhere covers the surface of land areas, carries a surprisingly large amount of water. After rain the interspaces of the soil will become uniformly occupied with water and gas; if the rate of rainfall is greater than the rate at which the water can pass through the pore spaces of the soil, it remains on the surface as pools or runs off the ground as surface flow. After seepage or the drainage of the water through the soil to the ground water plane of saturation has ceased, there will be found, provided the soil is uniform, commencing from the surface an increased quantity of water in each successive layer of soil, that is the water concentration in the soil in lbs. per cubic foot will increase with the depth of the soil. The water-retaining power of a soil is closely related to the total surface area of the soil particles per cubic unit; if a coarse and a fine soil are in contact, not one superimposed above the other, the quantity of water held in the coarse soil will be less than that held in the fine one, that is, the capacity of holding water of the two soils depends on the number and size of the capillary spaces of the soils. By capillary space is meant that space which is near the point of contact of two soil grains, and not any interstitial space in the soil. In a soil of fine texture the soil grains might be so close together as to make all the interstitial spaces capillary. The surface of the soil particles being clean, water has no difficulty in flowing over the surfaces, and the water by capillary action clings to the soil grains in the form of films, one surface being in contact with the soil grain and the other exposed to the air; as the surface of the land dries the water near the surface is evaporated, the curvature of the water films in the immediate neighbourhood will thereby be increased, and water will be drawn up from the next lower layer, and so on; it takes time for the water to move up these various layers. When rain falls on a dry soil the surface tension is diminished, and the greater tension below pulls the moisture down, even when the force of gravity would not be sufficient to do so; if the fall of rain is light, the moisture, after penetrating some distance, is again evaporated when the upper surface dries. Water held in the soil by surface tension is called the water of imbibition or quarry water; if more water enters the soil the film thickens until finally

when saturation is reached, all the spaces between the soil particles are filled with water, surface tension is reduced to zero, and gravity alone acts on the water. When this limit of the capacity of any soil for holding water is reached, water will flow, and becomes ground water, or the water of saturation.

18. The rate at which water leaves the soil during dry periods depends on a law similar to that which governs many processes, such as the loss of heat from warmer to cooler bodies, that is the quantity lost per unit of time will depend on the amount of water in the soil, and is consequently greater after rain; it is influenced by changes in temperature and varies inversely as the humidity. A soil possessing a greater surface area of soil particles per cubic unit will lose water less rapidly than one possessing a less surface area of soil particles per cubic unit, that is a *soil possessing not more than 2000 square centimetres surface* area of soil particles per cubic centimetre will lose water more rapidly than a soil possessing 4000 to 6000 square centimetres total surface area of soil particles per cubic centimetre.

This explains why clay soils retain their moisture for a longer period of time than more loamy or gravelly soils, and why a crop in heavy clay soil will wither when the soil below root range still contains abundant water, as the water cannot move up fast enough to meet crop requirements; also why a crop will mature in some soils with limited assistance from rain or irrigation, whereas in other soils the same crop will require constant irrigation or rain. In the case of sand, conditions vary; sand and sandy soils not exposed at the surface lose water rapidly, but when exposed at the surface at first the loss will be rapid, but this class of soil dries so effectually at the surface that several inches become air dry; the soil in which surface tension is able to act is, therefore, protected by a layer of dry material through which water passes as a gas by diffusion and not in liquid form by surface tension, and this process is extremely slow. In an experiment made by the Department of Agriculture, United States, the loss of water by gaseous diffusion through 2 inches of dry sand amounted to 1·4 inches to 4·3 inches in twelve months; consequently, after the surface 2 or 3 inches of a sandy soil have become really air dry, the loss from soil evaporation is very considerably reduced. A large area and great depth of sand forms, therefore, a natural reservoir.

Similarly, hoeing the soil so as to form 2 or 3 inches of air-dry, friable earth over the soil checks the evaporation of moisture from the soil and conserves it. In a thoroughly dry surface where the soil in its upper layers is so dry as to be deplete of moisture, evaporation from the soil is reduced to a minimum.

The depth from which water tends to move upwards through the soil varies with its texture and structure. It may be said broadly that under average conditions capillarity acts freely from 4 to 5 feet in depth, and fairly up to 10 feet, and extremely slowly below that depth. Dr. King, in the "Nineteenth Annual Report of the United States Geological Survey," Part II., states that where the surface soils are very coarse, and where the ground water plane of saturation is at a depth exceeding 8 feet below the ground surface, nearly the whole rainfall passes at once below the level at which it is possible for capillary action to bring it to the surface. Experiments made by Dr. Leather in the alluvial soil of Pusa, North India, composed of 2 feet of loam, next 2 feet sandy loam, and below that 12 feet of stiff clay, showed that 7 feet was the limit of depth from which water tended to move upwards.

19. Transpiration by vegetation increases the loss of water from the soil, the amount of water required for a crop equals the amount transpired by the crop plus the soil evaporation during the crop period. If the crop is a "good crop," the soil evaporation will be about half what it would have been from open fallow land. In Pusa soil, Dr. Leather estimates the amount of water consumed by a wheat crop during its season from November to March to be 10 to 11 inches on the ground, of which the soil evaporation during the period was 2½ to 3½ inches, the difference being the amount transpired by the crop. In Cawnpore soil, which contains more clay than Pusa soil, a five-month irrigated wheat crop—season, November to March—consumed an equivalent of 20 inches depth of water on the ground. The actual amount transpired by the crop was about 9 to 10 inches; the irrigation increased the soil evaporation. The diagram (Fig. 1) shows the amount of water consumed by an oat crop compared with soil evaporation from fallow land during the same period. The crop was not irrigated. The vertical scale shows the depth of soil in feet, and the horizontal scale gives the water concentration in the soil in lbs. per cubic foot for each foot in depth ("Memoirs of the Department of Agriculture in India," Chemical Series, vol. i., No. 10). Grass lands consume a considerable amount of water, while, on the other hand, forest cover, more especially the litter of a forest, may decrease soil evaporation by nearly seven-eighths of that in an open field, due to impeded air circulation, low temperature, and

the moist condition of forest air. Experiments in America show the relation between evaporation from bare soil to that of woods and forest litter to be as 1 : 0·4 nearly.

The following figures are results of experiments made in India on percolation and soil evaporation. In Pusa soil, which forms part of the Gangetic alluvium, which is exceptionally fine, with a low percentage of pure clay, which is highly calcareous, and which holds 25 lb. of water of imbibition per cubic foot, after drainage has ceased, Dr. Leather found the loss by soil evaporation on fallow land from 19th September, 1906, to 15th June,

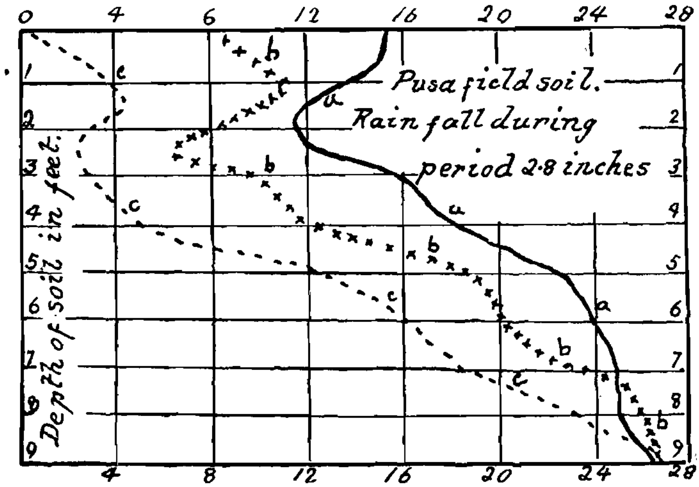


FIG. 1.—Water Concentration in the Soil, lbs. per cubic ft.
aa. Initial moisture in soil, 8th November, 1907, after the monsoon.
bb. Moisture in soil, 31st March, 1908, fallow ground.
cc. Moisture in soil, Oat-land harvested 31st March, 1908.

1907, to be 20 inches. The effects of light falls of rain during this period was to increase the water in the first foot of soil without penetrating deeper, and eventually to increase the rate of evaporation. The rainfall recorded at the places during the period was: 19th September to 20th October, 0·95 inch; 21st October to 7th January, nil; 8th January to 15th February, 1·4 inches; 16th February to 27th March, 1·85 inches; 28th March to 9th April, nil; 10th April to 30th April, 0·89 inch; 10th May, 0·33 inch; 1st June, 1·75 inches. Total, 7·17 inches.

The temperature varied from 60° to 90° F. An analysis of Pusa soil shows—

Grains less than 0·002 millimetre,					3·9 per cent.	
Grains between	0·002 mm.	and	0·004 mm.		4·8 ,,	,,
,, ,,	0·004 ,,	,,	0·008 ,,		7·7 ,,	,,
,, ,,	0·008 ,,	,,	0·016 ,,		9·4 ,,	,,
,, ,,	0·016 ,,	,,	0·032 ,,		40·4 ,,	,,
,, ,,	0·032 ,,	,,	0·5 ,,		34·2 ,,	,,
					100·6 ,,	,,

In the same soil the following results were obtained on drainage, or percolation, through 6 feet of soil :—

Date.	Rainfall. Inches.	Drainage. Inches.	Surface flow. Inches run off.	Evaporation from Soil. Inches.
Fallow land—				
1st Nov. 1906, to 31st Oct. 1907 .	39·72	6·96	4·02	28·74
,, 1908 ,, ,, 1909 .	75·70	28·36	8·32	30·46
,, 1909 ,, ,, 1910 .	32·30	6·41	Nil	25·89
Cultivated with maize—				
1st Nov. 1906, to 31st Oct. 1907 .	39·72	4·64	0·85	34·23
,, 1908 ,, ,, 1909 .	75·70	32·48	1·24	41·95

The cultivated land reduced the surface flow, and increased the soil evaporation losses. The percolation or drainage increased with the rainfall, and the soil evaporation to a certain extent increased with the rainfall.

In Cawnpore soil consisting of fine earth, more clayey than Pusa soil, and possessing an ordinary proportion of lime with irregular beds of nodular limestone, the following results were obtained from percolation experiments through 6 feet of soil :—

Date.	Rainfall. Inches.	Drainage. Inches.	Surface run off. Inches.	Soil Evaporation. Inches.
Fallow land—				
1st Nov. 1903, to 31st Oct. 1904 .	46·51	21·22	4	21·29
,, 1904 ,, ,, 1905 .	20·61	3·14	Nil	17·47
,, 1905 ,, ,, 1906 .	36·49	19·13	,,	17·44
,, 1906 ,, ,, 1907 .	20·89	3·04	,,	17·25
,, 1907 ,, ,, 1908 .	32·66	14·56	,,	18·10
Cultivated land—				
1st Nov. 1909, to 31st Oct. 1910 .	28·35	4·35	,,	23·82

Experiments at Rothamstead, England, the mean of twenty-five years give the following results for percolation and soil evaporation :—

Mean rainfall, 28·56 inches.

Depth of soil, 20 inches;	percolation, 14·16 inches;	soil evaporation, 14·40 inches.
,, ,, 40 ,,	,, 15·16 ,,	,, 13·05 ,,
,, ,, 60 ,,	,, 14·22 ,,	,, 14·34 ,,

Maximum year, 1878 to 1879. Rainfall, 41·05 inches.

Depth of soil, 20 inches;	percolation, 24·44 inches;	soil evaporation, 16·61 inches.
,, ,, 40 ,,	,, 26·03 ,,	,, 15·02 ,,
,, ,, 60 ,,	,, 24·38 ,,	,, 16·67 ,,

Minimum year, 1897 to 1898. Rainfall, 19·51 inches.

Depth of soil, 20 inches;	percolation, 5·95 inches;	soil evaporation, 13·56 inches.
,, ,, 40 ,,	,, 6·66 ,,	,, 12·85 ,,
,, ,, 60 ,,	,, 6·47 ,,	,, 13·04 ,,

In 1919 the following results were obtained. Rainfall, 33·05 inches.

Depth of soil, 20 inches;	percolation, 20·94 inches;	soil evaporation, 12·11 inches.
,, ,, 40 ,,	,, 21·38 ,,	,, 11·67 ,,
,, ,, 50 ,,	,, 20·97 ,,	,, 12·08 ,,

Mr. Charles Greives' experiments at Lee Bridge gives the following results :—

Rainfall, 25·721 inches;	percolation through soil,	7·582 inches.
,, 25·721 ,,	,, ,, sand,	21·406 ,,

At Camden Square the average annual soil evaporation from 1885 to 1919 was 15·51 inches.

In the basin of the Shannon, Ireland, the minimum annual rainfall has been found to be 45·71 inches, and the minimum evaporation from soil, 16·88 inches.

Mr. Mayer, in a paper read before the American Society of Civil Engineers, gives curves showing evaporation from land surfaces for various temperatures and rainfall (" Proc. American Society of Civil Engineers," Vol. LXXIX., 1915, p. 1081). Mr. Mayer's paper is worthy of study.

The depth at which the ground water plane of saturation is found below the surface of the soil largely influences the soil evaporation. Dr. King gives the following figures, showing the amount of evaporation from 1 square foot surface of fine sand for various depths of the ground water plane of saturation :—

Depth of ground water below surface in feet .	1	2	3	4
Evaporation from soil in lb. per day . .	2·37	2·07	1·23	0·91

With clay loam the following results were obtained :—

Depth of ground water below surface in feet .	1	2	3	4
Evaporation from soil in lb. per day . .	2·05	1·62	1	0·9

(*Vide* "Nineteenth Annual Report, United States Geological Survey," Part II., 1897 to 1898.)

Mr. Lee states that where the average depth of the ground water plane of saturation does not exceed 8 feet, soil evaporation, coupled with transpiration from vegetation, forms an important element of loss of ground water; he gives the following results of observations made at Independence, Serra Nevada, in 1911 ("Proc. American Society of Civil Engineers," Vol. LXXVIII., 1915).

Depth of ground water below surface of soil in feet	1·45	1·86	2·9	4·98
Soil evaporation, 12 months, in inches	48·80	44·89	40·21	13·43

Temperature of the air, 40° to 80° F.

The following figures give the results of Mr. Lee's experiments in grass and alkali land:—

Depth of Ground Water Below Surface of Soil.	Loss in Inches, by Soil Evaporation from Ground Water.		Total.	Remarks.
	Summer Average Temperature 70° F.	Winter Average Temperature 45° F.		
2·5	36·5	5·2	41·7	Summer, April to September inclusive. Winter, October to March.
3·5	29·6	4·0	33·6	
5·5	15·6	0·2	15·8	

To summarise: Percolation or the supply to the ground water depends on the rainfall, nature of strata pierced, and extent of exposed surface. It varies inversely with the soil evaporation, is greatest in winter, and during long-continued rains; it is least in summer with short, heavy showers of rain.

The deficiency of ground water will be felt most towards the close of a long, dry season, when the reserve of water furnished by the rains of the preceding wet season has been reduced to its lowest limit by the demands of the dry months. A failure of rain or a scanty rainfall during the rainy or wet season of the year is therefore more likely to cause a diminution of ground water, than a long dry summer.

The ratio between rainfall and evaporation from the soil, coupled with transpiration by vegetation, is dependent on such a great number of factors that no definite correlation exists between the losses from soil evaporation and transpiration with that of rainfall and temperature.

For climates with a mean annual temperature of 50° F. Vermeule gives an equation

$$E = 15 \cdot 5 + 0 \cdot 16R.$$

Where E is the annual vegetation and soil evaporation loss, in inches. R is the annual rainfall.

For climates with any other mean annual temperature T° F.

$$E = (15 \cdot 5 + 0 \cdot 16R)\,(0 \cdot 05T - 1 \cdot 48).$$

(" Report of the Geological Survey of New Jersey," 1894.)

From the results of experiments on land sodden with salt grass, Mr. Lee obtained the following formula :—

$E_1 = 54 - 7D$ (1st April to 30th September. Average temperature of the air, 95° F.).

$E_2 = 8 \cdot 2 - 1 \cdot 7D$ (1st October to 31st March. Average temperature of the air, 30° F.).

Where $E_1 + E_2$ are the losses from ground water in inches due to soil evaporation and transpiration.

D is the depth of the ground water plane of saturation below the surface of the soil in feet (" Proc. American Society of Civil Engineers," Vol. LXXVIII., 1905).

20. The quantity of water any particular soil or rock may yield does not depend on the quantity of water required to completely saturate the soil or rock. The water capable of being drawn off is that which the soil or rock contains over and above that which it is able to hold as water of imbibition (see paragraph 17), and the readiness with which the soil or rock will yield a supply when drawn on. Sand will hold 0·459 cubic feet of water per cubic foot of sand, when fully saturated, but the whole of this amount will not be available for supply ; the yield will probably be from 1·87 to 1·31 gallons per cubic foot. Col. Clibborn (" Roorker Treaties on Civil Engineering Irrigation Works in India," 1901) states that the actual quantity of water an underground sandy reservoir will hold depends on the character of the sand. It may be assumed at one-third the bulk of the sand, of which not more than one-fourth will drain in at once when a well is drawn on.

In the case of chalk the water of saturation equals 35 per cent. of the bulk of the chalk, or about $2\frac{1}{4}$ gallons per cubic foot ; the water of imbibition is 19 per cent., or 1·2 gallons per cubic foot. The yield, therefore, that may be expected from saturated chalk will be about 1 gallon per cubic foot. Chalk, however, readily absorbs water, but parts with it slowly. The yield from wells sunk into chalk strata is chiefly obtained from fissures and joints tapped by adits driven from wells sunk into chalk.

Except in desert areas where the rainfall is nominal, the "Recent" alluvial deposits yield inexhaustible supplies of water, which is contained chiefly in the beds of porous material such as sand or gravel. Large areas of sand, such as the sand dunes in Holland, provide sufficient water for a "Town Water Supply;" the only source being that portion of the rainfall of the district which has percolated to the ground water plane of saturation.

In the case of the older geological formations disintegrated and decomposed rock yield a limited supply of water. The hard, igneous rocks appear on the whole to disintegrate more easily than the rocks of sedimentary origin; the disintegration of igneous rocks often extending to depths of over 100 feet. In the Western United States in the gneiss of the archean period, which is highly metamorphosed, water readily finds its way into the numerous joints, and decomposition takes place along the ridges to depths of 80 to 100 feet. The underlying solid rock weighs about 170 lb. per cubic foot, while the thoroughly decayed rock weighs only 72 lb. per cubic foot.

In the Chittore district of the Madras Presidency, and in the adjacent Mysore plateau, where only a small depth of soil overlies the hard granitoid gneiss, which forms the base rock of peninsula India, the ryot or cultivator sinks wells into the granitic rock and obtains a supply in most years from the joints and fissures which traverse these rocks; village tradition based on the experience of successes and failures of past generations enables him to select a site for his well where he is most likely to tap fissured rock. In rocks of sedimentary origin, the more porous sandstones yield a fairly copious supply; in most other rocks the supply is chiefly obtained from channels opened in fissures and joints of the rocks by the chemical and the mechanical actions of ground water.

CHAPTER V.

PERMEABILITY OF SOILS: FLOW OF WATER THROUGH A POROUS MEDIUM.

21. All soils and rocks are permeable; even flint and agate show signs of the passage of water through them. The terms "permeable strata" and "impermeable strata" indicate only the degree of permeability of the strata. The flow of water through a saturated porous medium such as soil, sand, small gravel, and through the pore spaces of rocks, not through fissures, is effected through the small irregular pipes formed by the pore spaces in the medium. The flow may therefore be regarded as capillary, which is essentially the flow of water through pipes of small internal diameter at velocities which are less than the "critical velocity." The velocity of flow through these small pipes is given by the equation—

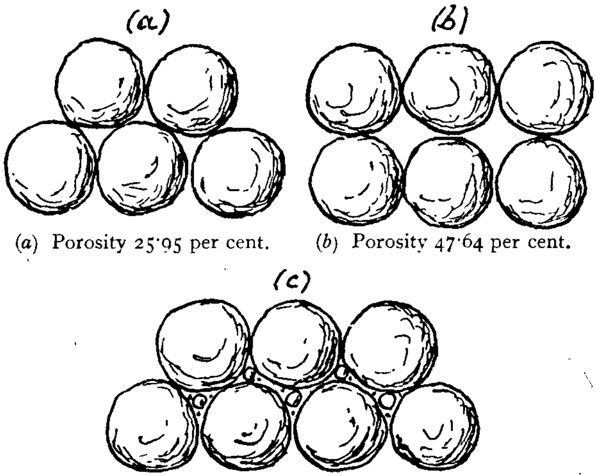
$$v = cd^2 \times \frac{h}{l} \times \frac{1}{\mu},$$

where c is a constant,
 h is the pressure head,
 l is the length of the pipelet.
 d is the diameter of the pipelet,
 μ is a coefficient of viscosity depending on the temperature of the water.

In a porous medium d and l cannot be measured, but they bear a certain ratio to the length of the medium traversed by the water, and the diameter of the minute particles or grains forming the medium. We may, therefore, consider that the flow of water through a saturated porous medium depends on the square of the diameter of the grains forming the medium, assuming these grains to be spheres. Ordinary sand has grains averaging in size from 0·3 mm. to 0·4 mm. Blown dune sand, the finest material usually spoken of as "sand," has size of grain varying from 0·15 mm. to 0·2 mm. The size of grain of a water-bearing sandstone may average 0·15 mm. An argillaceous soil may have size of grain varying from 0·002 mm. to 0·032 mm. Very fine silt may have size of grain ranging from

0·001 to 0·003 mm. Consequently, if *h* and *l* are constant, the velocity of flow of water through sand and sandstone will be many thousand times greater than the velocity of flow through compact argillaceous soil and fine silt. Hence we call sands and sandstones permeable, and clay soils impermeable. It must be understood that the above remarks apply to a saturated medium where gravity alone acts on the water.

The quantity of water flowing through a medium per unit cross-sectional area will depend on the porosity of the medium, the greater the porosity the greater the flow. If the grains forming the medium were all of uniform size, the porosity would



(*a*) Porosity 25·95 per cent. (*b*) Porosity 47·64 per cent.

(*c*) Porosity less than 25·95 per cent.

FIG. 2.

vary between 25·95 per cent. and 47·64 per cent. According as the soil grains are arranged as (*a*) or (*b*), *vide* Fig. 2.

If the water contained in the soil or sand exceeds that required for complete saturation, the soil loses its stability, becomes light, and has a tendency to flow. Col. Clibborn states from observations made on the change of condition of large horizontal surfaces of sand under varying heads of pressure, "it was found that the texture of the mass of sand became light and porous to a marked degree under high heads, so that a heavy substance placed on the sand would sink some distance, and, also, the sand flowed readily with the gentlest horizontal current." This phenomenon is often observed in the sandy beds of Indian rivers after the flood season is over. In places where the sub-soil water is forced to the surface, the sand loses its stability so much so that horse and rider often flounder in what appears to be a quicksand, but which is in reality a slowly moving stream of super-saturated sand.

Soil with over 50 per cent. voids, and fully saturated so that every pore space within the soil is filled with water, is unstable, and under pressure will act as a liquid. In soft saturated mud the per cent. of voids is 70. These conditions of soil require to be considered in the case of the impermeable core of an earthen reservoir dam, as even if the core material be so fine that the soil grains average 0·002 mm. in size, impermeability cannot be secured unless the material is subject to such compression as to reduce the percentage of voids in the mass to a minimum.

22. In "Recent" geological formations no other source for a water supply will be generally considered than beds of sand, or similar material; beds of gravel are rare, and in the majority of cases a bed of water-bearing sand is the source of supply. In the graphic analysis of a sample of sand taken from a strata of water-bearing sand, which is proposed to be utilised as a source of water supply, the total per cent. by weight of the sample passing through a sieve of a certain gauge is represented as an ordinate to the size of grain as abscissa. A coarse sand is indicated by a large abscissa compared to the ordinate, and a fine sand by a large ordinate compared to the abscissa. It is usual to grade sand by a series of sieves of a certain number of meshes to the linear inch. The table below shows the relation between the sieve number or number of meshes to the inch to the corresponding diameter of the sand grains in millimetres. That is, the width of the sand grain, and not its length, is assumed as its diameter.

Sieve No.	Size of Grain in Millimetres.	Sieve No.	Size of Grain in Millimetres.	Sieve No.	Size of Grain in Millimetres.
200	0·100	80	0·220	20	0·960
190	0·105	70	0·240	18	1·100
140	0·135	60	0·320	14	1·520
120	0·155	50	0·390	10	2·040
100	0·180	40	0·460	6	3·900
90	0·200	30	0·710	—	—

Mr. Allen Hazen classes sands by what he terms the effective size of the samples. The effective size, or E.S., of a sample of sand is such that 10 per cent. by weight of the material is of smaller grains and 90 per cent. of larger grains. His reasons for such a classification is that in a mixed material containing particles of various sizes, the water is forced to go round the larger particles and through the finer grains which occupy the intervening spaces, and so it is this finest portion which mainly determines the frictional resistance, the capillary attraction, and, in short, the action of sand in almost every way.

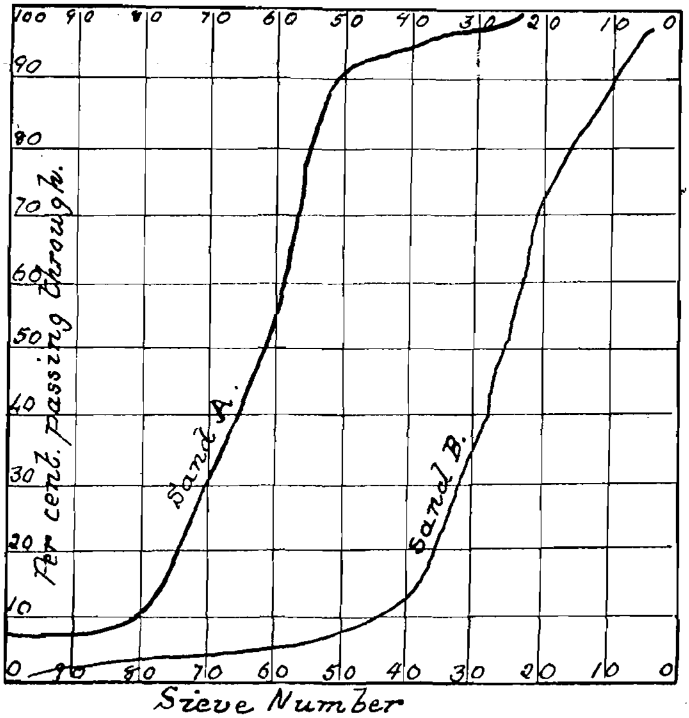


FIG. 3.—Sand Analysis.

Sand A. Finer 10 per cent. sieve 81. Finer 60 per cent. sieve 62.
Sand B. " " " " " 40. " " " " " 20.
Sand A. E.S. = 0·22 mm. U.C. 81/62 = 1·31.
Sand B. E.S. = 0·46 mm. U.C. 40/20 = 2.

The Uniformity Coefficient, or U.C., of a sample of sand is the ratio between the sieve number separating the coarser 90 per cent. from the finer 10 per cent., and the sieve number separating the finer 60 per cent. from the coarser 40 per cent. If the size of grains were all of the same size, the Uniformity Coefficient of the sample would be unity, and the porosity of such a sand *in situ* would vary between 25·95 and 47·64. If smaller grains are introduced, by suitable grading the per cent.

of voids can be considerably reduced (*vide* Fig. 2 (*c*)), and the Uniformity Coefficient would be increased. The Uniformity Coefficient of a sample of sand is thus an indication of the ratio between the sizes of the larger and smaller grains, and in a measure indicates the porosity or denseness of the sand bed from which the sample is taken. In a good water-bearing stratum of sand, the Effective Size of a sample should lie between sieve Nos. 30 and 60; and the Uniformity Coefficient should not generally exceed 3. The following are examples of sand analysis (*vide* Fig. 3) :—

Sand A.—Sample taken from a stratum of fine water-bearing sand, which was struck by an experimental well. The yield from this bed was small, and the sand was easily "blown" (*vide* para. 65) at a moderate pumping head.

Passed through	a No.	20	sieve,	100	per cent.
,,	,,	30	,,	98	,,
,,	,,	40	,,	96	,,
,,	,,	50	,,	92	,,
,,	,,	60	,,	52	,,
,,	,,	80	,,	8	,,
,,	,,	100	,,	8	,,

E.S. = 0·22 mm. U.C. = 1·31.

Sand B.—A coarser layer of sand struck below sand A, yielding a more copious supply and not easily "blown."

Sieve No.	Per Cent. Passed Through.	Sieve No.	Per Cent. Passed Through.	Sieve No.	Per Cent. Passed Through.
6	96	30	34	80	3
10	88	40	10	100	Nil.
16	80	50	8	E.S. = 0·46 mm.	
20	60	60	4	U.C. = 2.	

23. As already stated, paragraph 21, the velocity of flow of water through a porous medium depends on the diameter of the soil grains of the medium, the length of the medium traversed by the water, the head or pressure producing flow, and the viscosity of water, which varies inversely as the temperature of the water. The quantity or rate of flow depends on the porosity of the medium.

In paragraph 21 the velocity of flow of water through a porous medium is stated to be—

$$v = cd^2 \times \frac{h}{l} \times \frac{1}{\mu}.$$

where c is a constant;

d the diameter or effective size of the soil grains of the medium;

h the difference of pressure at the ends of and just inside a cylinder of the medium of length l.

μ co-efficient of viscosity depending on the temperature of the ground water.

If A be the cross-sectional area of the cylinder at right angles to the direction of flow;

p a coefficient depending on the porosity of the medium;

q be the quantity or rate of flow—

$$q = \mathrm{A}v \times \frac{1}{p}$$

$$\therefore q = cd^2 \times \frac{h}{l} \times \frac{\mathrm{A}}{\mu p}.$$

$$\therefore q = c\frac{d^2}{\mu p} \times \frac{h}{l} \times \mathrm{A}.$$

Professor Charles Slichter gives the following values for p and μ ("Nineteenth Annual Report United States Geological Survey," 1897 to 1898):—

Porosity Per Cent.	Value of p.	Porosity Per Cent.	Value of p.	Porosity Per Cent.	Value of p.
26	84·29	33	38·63	40	20·30
27	74·05	34	34·75	41	18·73
28	65·93	35	31·55	42	17·27
29	58·90	36	28·79	43	15·96
30	52·48	37	26·26	44	14·75
31	47·12	38	24·09	45	13·71
32	41·76	39	22·11	46	12·75
—	—	—	—	47	11·82

Values of μ for temperature of ground water t degrees Centigrade:—

t.	μ.	t.	μ.	t.	μ.	t.	μ.
0	0·0178	5	0·0152	10	0·0131	15	0·0114
1	0·0172	6	0·0147	11	0·0128	16	0·011
2	0·0166	7	0·0143	12	0·0124	17	0·0109
3	0·0161	8	0·0138	13	0·0120	18	0·0106
4	0·0156	9	0·0135	14	0·0117	19	0·0103

For other values of t, the value of μ can be obtained by the formula—

$$\mu = \frac{0{\cdot}0178}{1 + 0{\cdot}0337t + 0{\cdot}00221t^2}.$$

The values for p and μ given above show that the porosity of the strata and the temperature of the ground water have a marked effect on the flow of ground water.

If q represents the discharge in cubic feet in twenty-four hours, the formula becomes—

$$q = 289{\cdot}73 \times \frac{h}{l} \times A \frac{d^2}{\mu p},$$

where h and l are measured in feet, A in square feet, and d the effective size of the soil grains in millimetres.

If $M = C \times \dfrac{d^2}{\mu p}$; $q = M \,.\, A \,.\, \dfrac{h}{l}$; and if A, h, and l are each equal to unity, M is that quantity of water which would be transmitted in a unit of time through a cylinder of soil one unit in length, one unit cross-sectional area, and under one unit head, or difference of pressure, at the ends of and just inside the cylinder. M may therefore be called the "modulus" of the soil. The equation fails to hold good for high pressures, as probably capillary flow is destroyed. The equation also fails to hold good for beds of coarse gravel exceeding 3 mm. in effective size. Mr. Allen Hazen states that in such gravel beds the velocity of flow through the gravel varies as the square root of the head, and not directly as the head, and the velocity with a given head does not increase as rapidly as the square of the effective size. The influence of temperature is also less marked.

Col. Clibborn, in experiments with a pipe 100 feet long and 2·5 square feet sectional area, packed tightly with sand, found that for heads varying from 1 foot to 19 feet, the discharge curve was practically a straight line. He obtained values of M in cubic feet in twenty-four hours for the following Panjab sands, the units being 1 foot length of cylinder of soil, 1 foot head of water, and 1 square foot sectional area of the cylinder of the soil.

Khanki Sand.—Angle of repose, 33° 3′; specific gravity, 2·652; per cent. of insoluble matter after sulphuric acid treatment, 90·8; per cent. removed by mechanical analysis, 42·3. *M = 30.*

Jamro Sand.—Angle of repose, 33° 88′; specific gravity, 2·704; per cent. of insoluble matter after sulphuric acid treatment, 88·8; per cent. removed by mechanical analysis, 83·1. *M* = *42*.

The temperature varied from 67° to 74° F.

The actual discharges were—

Length of pipe, 100 feet = l; head, 19 feet = h; area, 2·5 square feet = A.

In the case of Khanki sand q = 14 cubic feet a day.

$$q = \mathrm{MA}\frac{h}{l} \text{ whence M} = 30 \text{ nearly.}$$

In the case of Jamro sand, q = 20 cubic feet per day, whence M = 42. As pointed out by Mr. W. B. Gordon, if q = the discharge per square foot area of sand, l the length of the pipe of sand, and h the pressure head, $q = \mathrm{M}\frac{h}{l}$. Therefore, for any section of pipe (see Fig. 4 below), $q = \frac{dy}{dx}\mathrm{M}$.

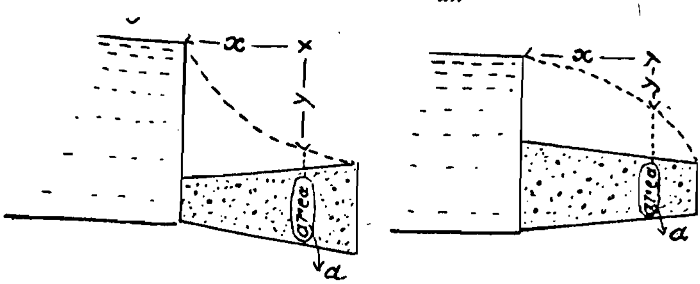


FIG. 4.

Total discharge $Q = qa$, $q = \frac{Q}{a} = \mathrm{M}\frac{dy}{dx}$,

$\therefore \frac{dy}{dx} = \frac{Q}{\mathrm{M}} \times \frac{1}{a}$. As Q and M are constant, $\frac{dy}{dx} = \frac{c}{a}$.

If a is some function of x,

$$y = c\int \frac{dx}{f(x)}.$$

The line of vertical slope or pressure in the pipe at any point x does not depend on the fineness or coarseness of the sand, but on the flow. If the flow is capillary, q depends on the effective size of the sand ("Technical Papers, Punjab Public Works Department").

Mr. Allen Hazen's formula to determine the flow of water through sand gives the value of M as

$$M = 3{\cdot}28\, cd^2 \frac{t + 10}{60},$$

where M is the flow in cubic feet in twenty-four hours;
d the effective size of sand grain in millimetres;
c a coefficient generally taken as 1000, but varies according to the condition of the sand, whether clean or dirty, and varies inversely as the uniformity coefficient;
t is the temperature of the ground water in degrees F.

Experiments have shown that a small quantity of clayey or dirty matter causes a diminution of flow through sand (*vide* p. 302, vol. xlviii., "Trans. Am. Society of Civil Engineers").

Mr. Baldwin Wiseman gives a formula for the flow of ground water ("Pro. Inst. Civil Engineers," Vol. CLXXI.). His formula and that of Professor Slichter, mentioned above, may be more accurate than Hazen's formula in small scale experiments, but involve laborious work in determining coefficients. As in actual practice porosity and other qualities of soil vary from point to point, Hazen's formula appears to be sufficiently accurate for preliminary investigations, if samples of the water-bearing beds are obtained and analysed as shown above. M is, however, best determined by actual yield tests of wells sunk into water-bearing beds, as will be explained in the chapter on "Percolation Wells."

The flow of ground water is extremely slow. Col. Clibborn estimated that in the Gangetic alluvium composed of beds of sand, loam, and clay, and extending to considerable depths, the slope of the ground water plane of saturation is about 1 in 250, and the velocity of a solid column of water of the same area as that through which percolation occurs is about a mile a year. Observations by American and French engineers confirm Col. Clibborn's estimate.

24. *Porosity of Soils.*—The most compact sand has a porosity of 26 per cent. of the total volume. Fairly uniform sand has a porosity varying from 35 to 40 per cent.

Sand and gravel	porosity	varies from	25 to 30 per cent.
Chalk	,,	,,	14 to 44 ,,
Sandstones	,,	,,	4·4 to 28·26 ,,
Limestones	,,	,,	0·58 to 17 ,,
Dolomite	,,	,,	2·9 ,,
Granite	,,	,,	0·02 to 1·5 ,,

2·704; per cent. of insoluble matter after sulphuric acid treatment, 88·8; per cent. removed by mechanical analysis, 83·1. $M = 42$.

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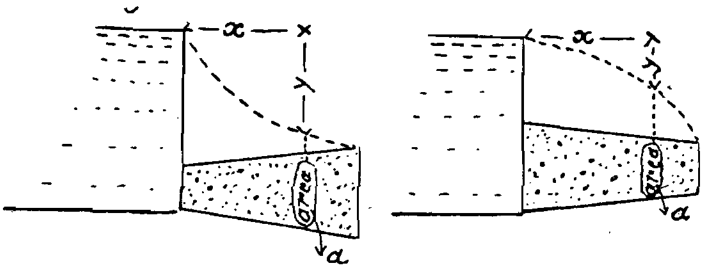

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CHAPTER VI.

GROUND WATER AND SPRINGS.

25. Water, perhaps the most important substance in Nature, is in a constant state of change and movement, by which its purity and consequent fitness for performing the various functions to which it is destined is preserved. In the ocean, that great ultimate recipient of the larger proportions of the rivers and streams which flow over the earth's surface, the great difference of temperature between the Poles and the Equator causes a continued interchange of cold and warm streams; and, in like manner, there is a perpetual movement upwards from the surface of the sea by evaporation, and downwards again by the flow of water, which, having been condensed, falls as rain or snow on the earth, and returns eventually to the great reservoir from whence it proceeded. Simple as the processes are, the result is most important to organic life, as a constant and sufficient supply of this vital fluid is thus brought everywhere within the reach of organic action, either as springs, rivers, or lakes; and when this remarkable circulation is contemplated, we can scarcely wonder at the speculations of Keferstein, who saw in the world itself a living organism.

A larger portion of the rainfall on the earth percolates through the surface to a greater or less depth in proportion to its porosity. In clayey soils this passage of water is slow, and the surface in wet weather becomes moist and clammy, and in dry forms a crust fissured by cracks. In sandy and gravelly soil the passage is quick, and the surface keeps comparatively dry; but if the soil be not very deep, and the water be received on a more retentive substratum, the readiness with which the moisture is restored by soil evaporation prevents an injurious aridity, and in consequence this condition of the surface is more generally favourable for vegetation than an impervious soil. If, on the other hand, the sand or gravel be deep and rest on an inclined impervious substratum, the water of saturation is rapidly removed, and a general aridity of surface is produced. These considerations naturally lead to a perception of the theory of springs.

26. The simplest case of a spring is that of a hill with a sandy top resting horizontally on an impervious base. During wet weather the sand becomes saturated, and the water sinks downwards till held up by the impermeable stratum. The water, therefore, presses downwards and outwards, and escapes as springs at the line of junction of the permeable and impermeable strata (*vide* Fig. 5). This is the most simple and frequent cause of springs. If the strata are not horizontal but inclined, the springs will be most abundant and continuous on the lower side. The resistance offered to the flow of water through the sand causes the ground water plane of saturation to assume an inclination; and this slope will vary with the discharge of the spring, which in its turn depends on the character of the grains forming the sand, and the porosity of the material. The level of the ground water plane of saturation will assume a slope as

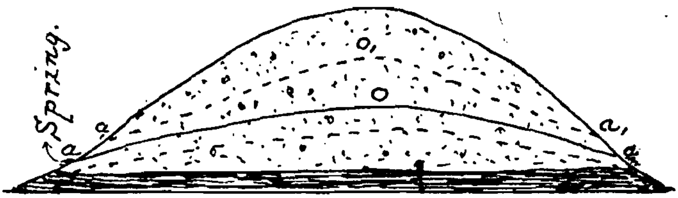

FIG. 5.

aoa, and the supply to the springs at *a* and *a* will depend on the amount of rainfall which percolates to the level of saturation. During rainy weather the ground water plane may rise, and springs may issue from a_1 and a_1. In dry weather, or after a prolonged dry season the ground water plane will get lower and lower, and the springs will diminish or will fail entirely if the gradient is not sufficient to produce flow. Observations made in water-bearing areas of sand show that in the sand dunes of Holland the slope of the ground water towards the collecting channels is 1 in 200. Mr. (now Sir) Alfred Chatterton states that in the spring channels of the Palar River, South India, where the slope of the ground water plane reaches a gradient of 1 in 250, the water is unable to move through the sand with any appreciable velocity.

It has been seen that whilst part of the rain falls on the earth's surface and runs off, another part filters through it, and this latter part, where collected together in any cavity of the less pervious substratum, forms a reservoir of water. Even on the sides of mountains, especially in damp climates, this process is constantly exhibited; and whilst the general surface becomes wet and boggy, numerous springs are seen wherever an inequality has led to an accumulation of water, and these, issuing as scarcely perceptible rills, go on gradually increasing as they join with others, and finally emerge in the greater valley as considerable streams. It becomes evident that springs will become superficial, small, numerous, but very temporary where the permeable stratum is very shallow, and the inequalities of the impermeable substratum slight. Where a permeable stratum with a limited gathering ground has a sufficient depression at some point to cause the line of saturation to sink occasionally below the level of the outcrop, the outflowing spring is intermittent, and the time of the appearance of such springs can be accurately predicted by observing the rise of water in the neighbouring wells sunk in the stratum.

In addition to the water which forms the superficial springs on a mountain-side, a portion may pass between the underlying rock, and the superficial matter above it, whether the latter be a stratified deposit or ordinary detritus resulting from the simple decomposition of itself; or should the overlying deposit be moderately porous, some of the water may pass directly through it to the underlying rock, and in either of these cases reservoirs of water will be formed in any great depression of that rock. This is a case which may be expected to occur in granite and highly metamorphic rocks; and in the former, in which open fissures are rare, whilst superficial disintegration, especially in hot climates, has proceeded to a great extent, it affords the only chance of meeting with deep-seated springs. Its application is shown in Ceylon; the underlying rock is a metamorphic horn-blende or syenitic gneiss, the outcropping edges of which have undergone much original modification, and is therefore supposed to form an undulated surface (*vide* Fig. 6), the hollows being filled by a detritus proceeding from the disintegration *in situ* of the more felspathic surface. From the mere inspection of the figure, it is evident that whatever may be the origin of the matter filling up the inequalities of the underlying rock, the water either in part percolating through it, or passing between it and the surface of the sound rock, must accumulate in the hollows, and that in consequence it may be necessary to sink at *b* to 80 feet for water, although at *a* it is found at 40 feet; and, further, that should the rock under *b* slope gradually off and become exposed in a valley, or on the side of a hill, the water may all be carried off as quickly as supplied, and produce, therefore, no permanent spring: circumstances which render the search for water in such cases very precarious. It may be further added that a rising or projecting spring can only be expected where the water passing between the detritus and the rock is pent up by them, and thus affords a head of water; as, if it merely percolated through the detritus, the pressure can only raise the spring to the height at which the water stands in the reservoir or hollow.

In what was recently German East Africa, with a rainfall varying from 40 to 60 inches on the coast, and 25 to 30 inches inland, and where in certain areas there is no rain from June to November, the surface rock, which is almost entirely granite or gneiss, is invariably decomposed to a depth of 80 feet, at which depth water is struck by bore-holes carried down to the solid

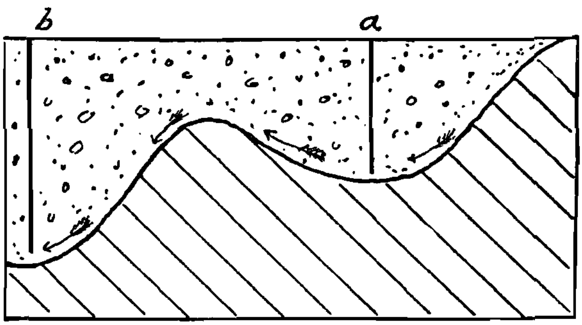

FIG. 6.

formation. Dr. Boyd Dawkins has shown its application in this country. Water-bearing beds formed by the decomposition of igneous rocks and crystalline schists resting *in situ* on the sound rock occur over a limited area in the British Isles, and in the Channel Isles; in Guernsey they form a cover 30 to 40 feet thick, riddled by veins and volcanic dykes; the detritus or decomposed rock occupy irregular hollows in the sound rock, and as a result of these conditions the water is stored in the porous decomposed rock in hollows, and there is no free circulation, as there would be in stratified water-bearing strata. A well might draw from its own reservoir and be independent of adjacent wells, and there is no possibility of obtaining a large supply from any one centre of pumping, although there might be many wells, each sufficient for local demands.

The other form of this case is where the hollows of the crystalline rock are filled by stratified deposits of sand and shale (*vide* Fig. 7). Here, as the shale has been worn away and the rock denuded at the summit, the water may gain access to the permeable stratum s_1 and produce a spring under bore-hole *a*, the water being held back by the projection of the rock to the left of it. Where water has saturated the whole of this permeable stratum, it will rise over the projecting rock; but if the stratum is open to the valley below no permanent spring may be produced under bore-hole *b* (Fig. 6), unless the stratum s_1 extends for a great distance beyond bore *b*, so that the resistance to flow in the length of the stratum to be traversed before its exposed face is reached is sufficient to cause flow up the bore-hole *b*. Again, under bore-holes *a* and *b* there will be a second supply of water, due to the permeable stratum s_2; but as these lower reservoirs from their imperfect connection with the surface must require a considerable time to fill, their practical value will be

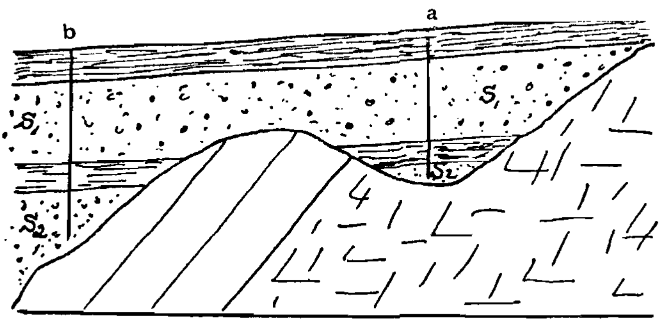

FIG. 7.

in proportion to their actual magnitude, or to the quantity of water previously stored by nature in them. In areas where crystalline and igneous rocks predominate, the choice of a site for a well is a matter of the greatest importance and of considerable difficulty. The massive and disintegrated igneous rocks hold little interstitial water, therefore we may regard the soil and sub-soil of the disintegrated rock as the only reservoirs of water from which under ordinary circumstances a well can draw its supply. Therefore, though a well must in most places be blasted out of solid rock, it must be blasted out in a place where there is likely to be a considerable amount of disintegrated rock and surface soil at as high a level as possible above the well, so that the well may tap fissures communicating with the disintegrated sub-soil. Without a large reservoir of this nature supplies from igneous and crystalline formations are precarious, and are likely to fail altogether. In Western Australia it has been found in the greenstone and granite formations that cases have occurred where, in the early development of some mines, heavy supplies of water originally found have gradually diminished, and eventually failed.

27. In the preceding instances the accumulation of water has been considered to arise principally from that which flows over the underlying solid crystalline rock, but it may be also entirely due to that which enters directly from the stratified deposits, and is merely held back or dammed up by the more solid rock, as in Fig. 8. Here it is evident that the supply of water will be in proportion to the extent of surface on which the rain falls, and from which it is directed to the permeable strata s_1 and s_2. If the supply be abundant, the stratum s_1 will be kept saturated up to the line of the borehole a, and a constant spring obtained, but if it be only small and casual, there may be a spring during

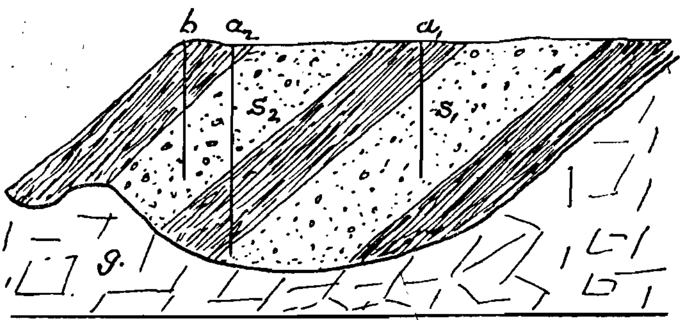

FIG. 8.

the rainy season, or whilst the water is percolating through the stratum, but none at a later period, and the chance of permanency will be increased as the borehole is carried nearer to the solid dam g, and the same reasoning will apply to the stratum s_2 and its borehole b. It may be observed also that a borehole a_2, which could only find a temporary spring in s_2 by being carried down through the intervening clays, might obtain a permanent one in s_1. In Cape Colony water is obtained from the "Karroo" beds of sandstones and shales, a transition group between the Palæozoic and Mesozoic eras. The sandstones are porous to a depth of about 100 feet, and then become compact and impervious. Intruding ridges of igneous rocks sometimes form underground dams, so that the selection of a site for a borehole, where the beds of sandstone and shale are almost horizontal, and are traversed by dykes of igneous rock, is not difficult. A careful examination of the dip and strike of the strata, and of the position of the walls of the impervious rock, points to a selection for a borehole which will drain the whole enclosed area. The question is complicated by faults and by folding of strata.

28. The case mentioned above leads to conditions where water is received and thrown up by stratified deposits arranged in the form of basins or troughs, and this may happen either where the basin is produced by an undulation or depression of the underlying strata, or where it occupies the valley produced

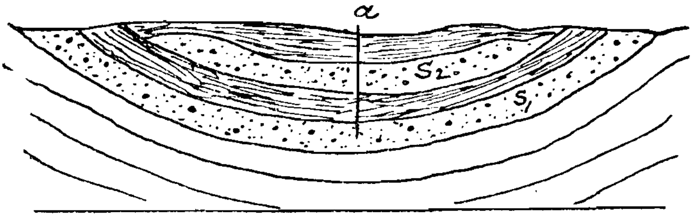

FIG. 9.

by the disruption of these strata by elevation, and as some precaution is necessary in reference to this distinction, each case will be considered separately. Fig. 9 is the first case where the permeable and impermeable strata have been deposited in a basin of undulation, and the water entering stratum s_1 is prevented from descending into the soil by the impervious stratum below, and from ascending by the impervious stratum above, so that it is pent up in the pervious stratum itself. An inspection

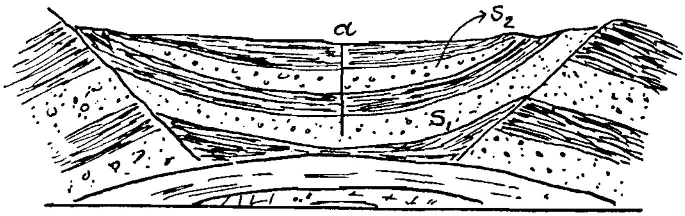

FIG. 10.

of the figure is sufficient to show that the nearer the borehole is made to the lower point of the valley, the more abundant and secure will be the supply. If, instead of one pervious stratum of sand or gravel, there are several, the reasoning would be the same, only it might happen that the upper layers are closed up by impervious layers passing over them, as in the figure, and therefore would be found unproductive of water. Fig. 10 is a basin formed within a valley of disruption or even of denudation, or which differs from the preceding only in this circumstance, that the boundary walls of the valley may in themselves be partly pervious, and therefore allow the water to escape. If such occur, the water cannot rise above the level of these discharging strata represented in the figure. And, again, secondary

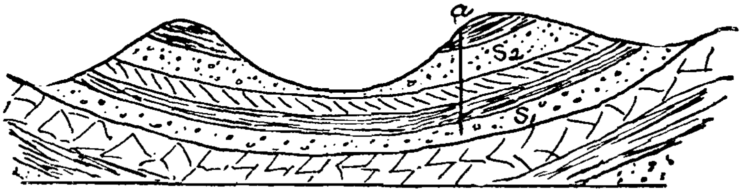

FIG. 11.

denudation may modify the basin deposit, and affect its supply, as in Fig. 11, where it is evident that any layers of pervious strata cut through by the denudation in the centre of the basin must discharge the water they receive into the inner valley of

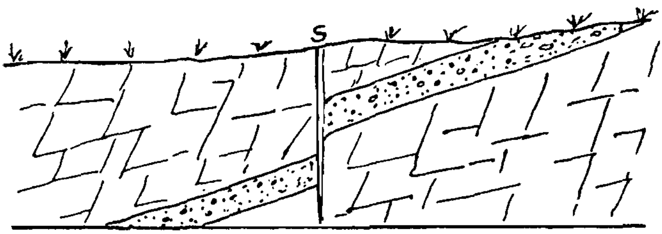

FIG. 12.

denudation, and no great supply can be expected until the lower layer, or at least the first layer not affected by the denudation, has been touched by the borer.

Faults may also materially affect the arrangement of springs, as in some cases when filled with impervious matter they may

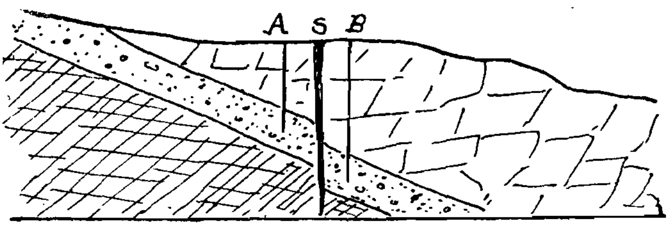

FIG. 13.

act as dams, and in others may discharge water as in Fig. 12. So that in boring in the vicinity of a fault, care must be taken to ascertain its condition; for if the fault be filled with impervious matter, well A (see Fig. 13), although not so deep-seated, may give a better supply than well B.

29. These examples are sufficient to guide the engineer in the application of principles to practice in every case, and he will at once see the great necessity of studying the geological as well as the physical character of the country in which he seeks for water. In granite and in most crystalline rocks, such a search must be very precarious. In stratified deposits, not metamorphosed, the occurrence of porous alternating with impervious beds brings the principle into operation; and in proportion as the porous beds are looser in texture, as in the Tertiary and Post Tertiary sands and gravel, and the arrangement of them is limited by a basin-like form, so will the chance of success increase until it becomes a certainty. A correct knowledge of the stratification at the outcropping of the strata must therefore become a sure guide to the engineer, and in his borings he will carefully compare the strata passed through with such manifestations of them on the surface, in order to judge whether he has arrived at or passed through any one of them. As an example, surface springs are generally indications of a fault, or the junction of a pervious and an impervious stratum, and this method of detecting boundary lines of this description may be generally depended on. Should the engineer not be able to find any of these basin-like deposits of looser material, his pursuit of water in more solid strata must be equally guided by a knowledge of these geological and physical peculiarities, such as, for example, as in chalk, and even in the Oolite districts, as in such cases the numerous fissures may permit water to descend until it is stopped by either a less fractured bed, or by some of the divisional clayey beds of such formation; and when once such bed or stratum has been discovered in any district, it becomes an index for the operation of the borer.

30. *Artesian Wells.*—A writer of Alexandria, writing in the sixth century, describes how, where wells sunk in the oasis of the desert to a depth varying from 500 to 1000 ells, water springs up from the orifices so as to form rivulets, from which farmers irrigate their fields. In the desert of Sahara the natives bore to a depth of 600 feet, and often succeed in finding water, which flows up in great quantities, the pipes being often hollow palm trees. In China artesian wells are largely used, the pipes being hollow bamboos.

It may be generally stated that artesian areas are found in the cretaceous and newer formations. The term "artesian" is, in this book, applied to wells or bore-holes which tap water-bearing strata superimposed and underlaid by impermeable strata, and which outcrop at such an elevation that water rises under pressure not necessarily to the surface, as opposed to a percolation well. Where a permeable water-bearing stratum is underlaid and overlaid by impermeable strata, measurements of the static water levels at the various wells, or the bore-holes with impermeable linings, sunk through the intervening strata to the permeable water-bearing stratum, enables contours of water pressure to be drawn. These contours define the hydraulic grade surface, and lines normal to these are the direction of flow. The intersection with the ground surface on these normal lines fixes the outcrop of the permeable stratum. Where the ground level is below the hydraulic grade surface, a boring sunk at this place to the water-bearing permeable stratum will be a "flowing" artesian well; borings sunk in ground above the hydraulic grade surfaces will be "non-flowing" artesian wells.

Artesian wells are only possible where geological conditions are favourable, and it is curious that this is the case both in London and Paris. About 2000 feet below the surface level of Paris the beds of green sand are tapped, and it is from this source the famous artesian wells of Grenell and Passy draw their supply. The artesian well at La Butta Aux Cailles, Paris, was commenced in May, 1866, and completed in 1903, after being interrupted for twenty-two years from 1870 to 1892. The strata encountered being sand, limestone breccia, and clay for 216 feet, then chalk to a depth of 1739 feet, beneath which the Gault clay and green sand were traversed. In 1898 a spring was struck at a depth of 1875 feet, but boring was continued further into the green sand to a depth of 1911 feet, and a copious spring was found yielding 15·4 gallons per minute, and rising to a height of 187 feet.

The artesian water-bearing beds of Queensland, Australia, composed of loose water-bearing sandstone, which are in parts hundreds of feet in thickness, separated by bands of clay and shale, outcrop along the western slope of the main watershed on the eastern side of the colony. Their dip is generally in a westerly and south-westerly direction, divided by outcrops of primary rock. A typical borehole, after passing through various beds of sandstone and shale, struck a water-bearing stratum of sandstone at 2370 feet below ground level, yielding 670,000 gallons a day at a temperature of 166° F., and having a static head of over 200 feet. The borehole at Charleville, in the same area, yielded 3,000,000 gallons a day, having a static head of about 240 feet. Nine years afterwards there was a material diminution in flow, and the static head fell to about 190 feet. It is obvious that when water is first struck in an artesian borehole, it flows with a velocity corresponding nearly to the static head at the ground surface; when the flow becomes steady it causes a diminution of pressure, and the amount of flow will continue to diminish until the pressure gradient towards the well adjusts itself to the volume of water discharged. Other causes of diminution of supply are the sinking of fresh well boreholes in the vicinity, and long-continued absence of rainfall on the permeable out-cropping area, particularly in those wells nearest to the out-cropping edges. Deep-seated artesian areas have not been discovered in Cape Colony, depths of 1500 feet having been tried without success.

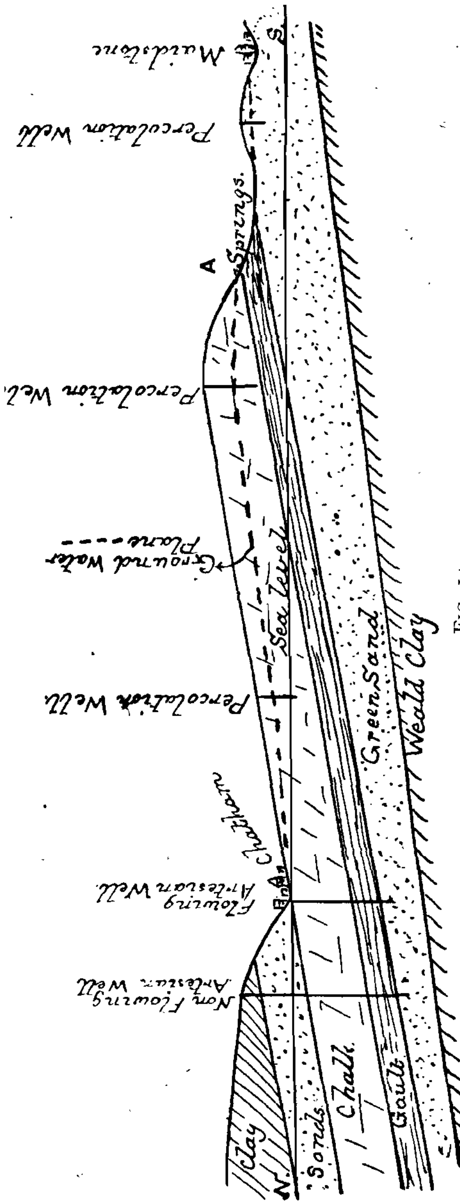

Fig. 14.

The temperature of the water from deep-seated springs varies. In this country the temperature from water from wells and bore-holes is 52° F. at a depth of 100 feet; 59° F. at a depth of 500 feet; 68° F. at a depth of 1000 feet; 76° F. at a depth of 1500 feet. For a potable water supply a temperature of about 55° F. is desirable.

31. As an illustration of the foregoing principles, a few cases may be cited. Along the North Downs the permeable chalk strata repose on the gault clay, with the result that springs issue at numerous points along the line of junction. In the neighbourhood of

Maidstone and Chatham, the formation consists of chalk some 600 feet in thickness resting on the impermeable gault clay about 200 feet thick, below which lie the sands, and sandstones of the lower green sand formation which rest on the Weald clay (*vide* Diagram 14). The rainfall which percolates into the chalk is checked by the sloping surface of the gault, and moves in a northerly direction. The lowest level to which the ground water plane of saturation is likely to fall is indicated by the outcrop of the gault clay in the south, and the sea-level at Rochester. Wells must be sunk below this line into the chalk to obtain a constant supply of water, and consequently the chalk plateau lying at the back of the North Downs suffers considerably for want of water, the wells being deep and expensive to construct. The wells sunk into the chalk are termed percolation wells. The lower green sand beds are very permeable, and are capable of containing a large quantity of water, and they are overlaid and underlaid by two impermeable layers of clay. The green sand beds slope downwards to the north, getting very much thinner as they go, and they expose a large surface south of the chalk escarpment round about Maidstone. The rain which percolates into the Maidstone area sinks downwards till checked by the Weald clay, and then travels northward down the slope, so that the greater portion of the green sand strata is saturated with water, the ground water plane of saturation being some height above sea-level. Consequently, borings at Chatham carried down through the chalk and gault tap an artesian spring, and the water will rise in the bore-pipe considerably above the level of the sea. In the bore-hole sunk further north through the clay, sands, chalk, and gault into the green sand formation, the water from the green sand beds will rise to a static level, the same height above the sea-level as that of the ground plane of saturation at Maidstone. The bore-hole will be a non-flowing artesian well. At A (Fig. 14) the springs will be intermittent, for as long as the level of the ground water plane of saturation is above the level of the outcrop of the gault, the spring will flow, and the flow will cease, when the saturation level falls below the level of the outcrop.

A different case is that of the gravel beds of the Darling range and the inland plane of Western Australia, which have a direct communication with the ocean, as evidenced by the large submarine springs occurring on the coast. At the Midland Junction, 22 miles inland from Perth, a bore-hole sunk through these beds produce an artesian supply. The friction of a few hundred feet of pipe discharging not very much above sea-level being less than the resistance to flow offered by the 20 miles of gravel beds.

32. Another source of water supply is where a sandy tract of land is surrounded or partly surrounded by the sea, and the soil contains large quantities of fresh water extending in the centre to several hundred feet below the sea-level, below which salt water is reached, which is also found near the sea, and in low-lying, drained lands at the surface. The fresh water thus floats on the salt water in the form of a basin with steep sides, and the supply is entirely dependent on the local rainfall which percolates through the sandy soil. When larger quantities are withdrawn than are supplied by the rainfall, the surface level falls, and salt water filters in from the sea. The island of Rameswaram, separating India from Ceylon, is supplied with water from a cup-shaped basin of fresh water which was found in a sandy waste plain situated a few feet above the level of the sea. In the centre of the island of Nordenney, on the shore of the North Sea, which is $1\frac{1}{4}$ miles wide at the place, a cup-shaped volume of sweet water was found extending to a depth of 190 feet.

CHAPTER VII.

RUN OFF OR SURFACE YIELD FROM A HYDROGRAPHIC BASIN

33. The relation of the amount of water running off the surface, or the surface yield from a hydrographical basin due to the rain falling on it, presents a problem to the civil engineer which still remains unsolved. The geological, physical, and meteorological conditions of river basins are so varied, that a search for a mathematical expression connecting the surface yield of a basin with the rain falling on it appears to be in vain. The surface yield of a hydrographical basin has already been defined (par. 15). It is usual to measure this yield either as a per cent. of the rain falling on the basin, or the losses for any period, usually a year, are estimated, or ascertained by direct observation, and the difference between the rainfall and the losses is the yield from the basin. Apart from the geological and physical conditions of hydrographical basins, the yield of each basin depends on the intensity of rainfall on each square mile of the basin, its duration, length of dry period before the rain, and whether the rain falls in the hot or the cold weather. The surface yield may be increased by a network of furrows or small drains to lead the water quickly to the main channel. As a general rule, it may be said that when the annual rainfall on a basin does not exceed 10 to 12 inches, the whole of it is lost in evaporation and transpiration, and causes no surface flow, except when it comes in violent storms.

34. In the case of tanks or small reservoirs in Southern India, Col. Montgomery, R.E., estimated the surface yield of their hydrographical basins as follows. He considered 10 inches of rainfall as the least annual average sufficient to cause water to run off the land, and gave as a rough rule the per cent. of annual rainfall that could be expected as run off or yield, as half the annual rainfall less 10 inches. That is, if the annual rainfall was 40 inches on the hydrographical basin of a tank, the annual surface yield that could be expected would be $\frac{1}{2}$ (40-10) or 15 per cent. of the rainfall, or 6 inches over the basin. If the annual rainfall was 110 inches, the annual surface yield would be

$\frac{1}{2}$ (110-10) or 50 per cent. of the rainfall, or a surface yield of 55 inches over the basin. The rule, he admitted, was a very rough one.

The following conditions for the United States may be generally accepted. The per cent. of annual rainfall which runs off a hydrographical basin is equal to the number of inches of annual rainfall, when the annual rainfall is 50 inches or less. For rainfalls of over 50 inches, 25 inches is lost by evaporation, transpiration, etc., and the balance is available as surface flow, e.g.,

Annual rainfall,	10	inches.	Surface yield,	10	per cent.	=	1	inch on the basin.
,, ,,	20	,,	,,	20	,,	=	4	inches ,, ,,
,, ,,	30	,,	,,	30	,,	=	9	,, ,,
,, ,,	50	,,	,,	50	,,	=	25	,, ,,
,, ,,	60	,,	,,	60-25	,,	=	35	,, ,,

For South Pacific conditions the following results are obtained :—

Annual rainfall,	10	inches.	Surface yield,	1	inch on the basin.
,, ,,	20	,,	,,	2·5	inches ,, ,,
,, ,,	35	,,	,,	10	,, ,, ,,
,, ,,	47·5	,,	,,	20	,, ,, ,,
,, ,,	57·5	,,	,,	30	,, ,, ,,
,, ,,	67·5	,,	,,	40	,, ,, ,,

The usual practice of waterworks engineers in the British Isles is to assume the surface yield due to the mean annual rainfall of the three consecutive driest years as the annual available supply, and to provide storage sufficient for a number of days, varying with the irregularity of the rainfall of the locality. For non-absorbent areas, the general rule, if adequate storage is provided, is to assume four-fifths of the mean annual rainfall to arrive at the mean of the three consecutive driest years, to deduct from 12 to 20 inches as losses, and to assume the resulting figure as the yield. The following table gives approximate yields that may be anticipated from annual rainfalls in temperate insular climates such as that of the British Isles :—

Annual Rainfall. Inches.	Losses. Inches.	Yield. Inches.	Yield as Per Cent. of Rainfall.
20	12	8	40
30	16	14	47 nearly.
40	19	21	$52\frac{1}{2}$
60 to 70	20	40 to 50	$66\frac{1}{2}$ to $71\frac{1}{2}$

Mr. Strange gives a diagram showing the per cent. of surface yield to rainfall for different classes of catchment in the Bombay

Presidency. He also gives a table, shown below, for calculating the approximate yield from a hydrographic basin from the daily rain falling on it :—

Daily Rainfall in Inches.	Per Cent. of Run Off when the Ground is		
	Dry.	Damp.	Wet.
0·5	0	10	14
1·0	5	14	20
1·5	7	19	26
2·0	10	25	34
2·5	15	32	43
3	20	40	55
4 and over	30 to 40	50 to 60	70 to 80

(" Indian Storage Reservoirs," W. L. Strange, 1904. Spon, London.)

The following rules were adopted by the Madras Irrigation Department for the classification of the state of humidity of the soil when using Mr. Strange's table shown above :—

(1) Rain required for transition from dry to damp—

$\frac{1}{4}$ inch fall	in the previous	1	day.
$\frac{1}{2}$,,	,,	,, 3	days.
1 ,,	,,	,, 7	,,
$1\frac{1}{2}$,,	,,	,, 10	,,

(2) For transition from dry to wet requires a fall **of $2\frac{1}{2}$ inches** in one day previous.

(3) For transition from damp to wet—

$\frac{1}{3}$ inch	in previous	1	day.
$\frac{1}{2}$,,	,,	2	days.
1 ,,	,,	3	,,
$1\frac{1}{2}$,,	,,	5	,,

For transition from wet to damp, half the rainfall noted in (3).

For transition from wet to dry, quarter the rainfall noted in (3).

For transition from damp to dry, half the rainfall noted in (1).

Sir Thomas Higham, some time Inspector-General of Irrigation in India, states that roughly it may be said that out of a total average rainfall of 35·5 inches for India, 60 per cent. is absorbed in sustaining plant life, in maintaining moisture of the soil, and in replenishing sub-soil water, or is lost by evaporation; and 40 per cent. flows off the ground. The figures given are at best approximations; in many rivers the per cent. of flow off the ground is considerably less than 40 per cent. The per cent. of the total rainfall on a hydrographical basin which flows off the ground as surface "yield increases" with the rainfall. In Australia, the Darling river, with an area of basin of 235,000 square miles, on which the annual rainfall varied from 26·81 in 1894 to 11·22 inches in 1902 (lowest on record), has a mean surface yield of 0·65 per cent. of the rainfall; the Murray river—area of basin, 408,000 square miles; mean annual rainfall on the basin, 15·56 inches—has a mean surface yield of 2 per cent. of the rainfall. Mr. Buckley's "Irrigation Pocket Book" (E. & F. N. Spon, London) gives numerous examples of "annual flow-off catchments" in different countries.

Mr. Mayer, in a paper read by him before the American Society of Civil Engineers (Vol. LXXIX., 1915, of the Proceedings), treats of the subject of run-off from rainfall very fully. He gives curves of evaporation from land and water surfaces, and ascribes the rainfall losses to be chiefly due to evaporation from land surfaces (*vide* par. 19).

35. The maximum continuous yield that may be expected from a hydrographical basin would be the correctly ascertained mean rainfall on the basin, less the correctly ascertained losses; but as years of rainfall in excess, and sometimes greatly in excess, of the mean enter into computation for ascertaining the mean, and the years of rainfall greatly in excess of the mean occur at long intervals of time, large storage would be necessary to impound the yield of years of rainfall in excess of the mean to cover the deficiency of years of rainfall below the mean. Thus a large outlay in the cost of the reservoir would be involved, without any very great increase in the available supply, and the loss from evaporation from the water surface of the impounding reservoir would be considerable.

Moreover, the rainfall in excess of the mean is often due to floods which last for a short period of time, and unless the impounding reservoir is of very large capacity, the greater part of the flood supply will be lost. On the other hand, it is not necessary to limit the available supply to the yield due to the year of minimum rainfall, as by taking the mean annual yield of three or four consecutive years of lowest rainfall as the "supply available," it would be possible to tide over the year of minimum rainfall by a comparatively small reservoir; and a somewhat smaller supply would be obtained, at a considerably less cost, than would be the case if the yield from the mean annual rainfall was assumed as the "supply available" from the hydrographic basin under consideration. It may be here pointed out that areas in this country free from pollution, and of sufficient area for present requirements are now becoming difficult to obtain, and engineers can no longer be satisfied with securing the mean yield of the three consecutive driest years.

36. In comparing and analysing the surface yields of hydrographical basins due to the rain falling on them, the period generally taken for comparison is that period of time in which the seasons complete their cycle, that is, a year ; but it is obvious that the calendar year is not suited for such comparison, and the period of time for our purposes should be what may be termed the "Water Year." The "Water Year" should begin when the ground water plane of saturation is at its lowest level, or at its highest level, but as it is not always possible to ascertain the mean calendar month in which these conditions obtain, the water year is generally assumed to begin when surface or stream flow is at its minimum or ceases altogether, and ends at a similar date the next year. If rainfall and surface yield are tabulated, starting from the calendar month, or the next succeeding month in which stream flow is nil, or at its minimum, it will be found that the connection between rainfall and surface yield are more regular than when results are tabulated by the calendar year. In the British Isles and in the United States of America the water year will begin about September. In India the water year will begin at the end of the dry weather period, generally about the 1st June. In further analysing the surface yield of a basin, the total yield of a water year may not always be a reliable guide as to the supply available, as during certain periods of the year there may be little or no yield, although the total yield of the year may have been sufficient for requirements, and a further division of the water year into seasonable periods seems necessary.

It is possible to ascertain from observations of rainfalls for a considerable number of years at a locality the wet and dry seasons of a year, and to divide the water year into periods when the relations of surface yield to rainfall are markedly different. American investigators divide the water year into three seasons, viz. : (1) The storage period during which evaporation and transpiration are small, the surface yield large, and during which period the ground water plane of saturation reaches its highest level ; (2) the growing period, when evaporation and transpiration are large, the surface yield is small and decreases to its minimum, or ceases altogether, and the ground water plane of saturation sinks to its lowest level ; (3) the replenishing period, when, with normal rainfall, the ground water plane tends to recover its level, streams begin to increase in flow and normal conditions are re-established. In the British Isles the replenishing period would be the beginning of the water year, and would include the months of September, October, and November. The storage period would include the months of December, January, February, and March, and the growing period would include the months April to August; and probably the same divisions of the water year would apply to the temperate zones of the United States of America. In the climates of the temperate zones the ground surface never becomes thoroughly dry, except after intense and long continued drought, which may occur once in thirty or forty years, so that the summer rainfall often influences the annual yield, but the bulk of the annual yield depends on the rainfall of the storage period. In tropical climates there are generally two distinct seasons of the water year (*vide* par. 2). The wet or rainy season, when the bulk of the annual rainfall is received, and the dry season, when little or no rain is received, except in thunderstorms, and the ground becomes thoroughly dry, so that the summer rain has little influence on the annual surface yield. In the equatorial rain belt there are two wet and two dry seasons in a year, and the divisions of the water year given above will require modification. In desert areas and arid zones the intensity of each individual fall of rain influences the surface yield, and no division of the water year is possible.

37. The conditions which influence the yield from a hydrographical basin are the amount and intensity of the rainfall on it, the slope of the ground surface, amount and nature of its vegetation, and its geological formation. The rain that falls on the basin is disposed of by—

(1) Transpiration by vegetation.
(2) Evaporation from the soil and from bodies of water.
(3) Appears as surface flow in the streams draining the basin.
(4) Percolates into the soil, and re-appears as surface flow after a varying period of time; or percolates too deep to re-appear as surface flow, augments the ground water, and eventually escapes to the sea, or continues to circulate in the interior of the earth.

Losses due to (1), (2), and (4) have already been dealt with (*vide* Chap. IV.). Of these losses the greatest are those due to soil evaporation and transpiration by vegetation. If it were possible to estimate these losses with any degree of accuracy, the surface yield would be the rainfall less these losses, but as the rate of fall influences the percolation, they are difficult to estimate, and, as will be shown, the loss and gain to surface flow by the action of the ground water complicates the problem.

The simplest and most accurate method of determining the surface yield from any basin is to actually measure the discharge of the stream draining it for a considerable number of years, so as to obtain the mean, maximum, and minimum discharges that may be expected in the periods into which the water year is divided. To neglect records of stream gaugings, even if approximately correct for rainfall records, which may be of far greater accuracy, and to estimate losses from imperfect data, cannot be considered a satisfactory solution of the problem; but as observations of rainfall are made in all countries, while gaugings of stream flow are few, it becomes necessary to ascertain the relation of yield to rainfall for any basin, by comparison of observed losses in neighbouring basins which are subject to the same meteorological conditions, or by actual stream gaugings for a few years. Data of reasonable accuracy showing the distribution of flow over several consecutive years are of more importance than accurate measurements covering a short period of time. The most satisfactory solution, under the conditions above described, would be the installation of a stream gauge on the watercourse draining the basin, working continuously for at least seven years. If the gauge is calibrated for the various stages of flow, it would be possible to compare the surface yield of the basin with the rain falling on it for the different periods of the water year for the years in which stream gaugings are available, and from the data thus obtained to deduce yields for the years in which rainfall records are available and stream gaugings are not.

38. The difficulty experienced in comparing rainfall with surface yield is the loss and gain to surface flow due to ground storage. That is, if—

R be the rainfall on a hydrographical basin for any period of the water year measured in inches;

y be the surface yield from the basin during the same period measured in inches on the basin;

L be the losses due to evaporation and transpiration measured in inches on the basin;

G be the gain or loss to y, due to ground storage, measured in inches on the basin;

$$y = R - L \pm G.$$

The loss from deep seepage is small compared with L, and may be neglected.

It is thus seen that L depends on the meteorological conditions, and G depends on the geological character of the basin.

If G could be neglected, on the assumption that the rainfall which percolates into the ground re-appears as surface flow, the surface yield y for any period of a water year would be R, less the observed or estimated losses from evaporation and transpiration. Thus,

$$y = R - L$$

if R be the annual rainfall and y the annual surface yield, using Vermule's equation (*vide* par. 19).

$$L = (15{\cdot}5 + 0{\cdot}16R)(0{\cdot}05T - 1{\cdot}48)$$

and $$y = R - (15{\cdot}5 + 0{\cdot}16R)(0{\cdot}05T - 1{\cdot}48).$$

The ground water losses are less important in large than in small areas, because a large portion of the rainfall may pass out of a small basin as ground flow, whereas in a large one, a great deal of the ground flow is returned to the surface as springs. The ground water may be compared to a subterranean reservoir which at various seasons of the year increases or diminishes the yield. In a "wet year" the ground water may be stored and passed on to the succeeding year; and in a dry year the ground water may be so depleted that the next year's rain may produce no augmentation to the yield from ground storage. This action of the gain or loss from ground storage is one of the causes of the variation in the yearly yield, and the variations are increased if there are two abnormal dry years, or two abnormal wet years in succession.

39. To show the effect of ground storage on the surface yield, an example is given of the gauging of the Thames at Teddington (*vide* "Proceedings of Inst. of Civil Engineers," Vol. CLXVII.). The area of the Thames basin above Teddington weir is 2,423,000 acres, the greater portion consisting of chalk hills, and consequently absorbent. The gaugings are the mean results of eighteen years, 1883 to 1900.

For comparison with temperature, hours of sunshine, and humidity, the water yield is divided into three equal parts. August, having the smallest flow, is selected as the first month of the water year. The water year is divided into—

Replenishing	period,	August to November,	122 days.
Storage	,,	December to March,	121 ,,
Growing	,,	April to July,	122 ,,

Rainfall, losses, and yield are given in inches in depth over the basin :—

	Period.			Total.	Remarks.
	Replenishing.	Storage.	Growing.		
Rainfall	10·44	8·38	7·58	26·38	S.H.D. = Sunshine hours per day during the period. It is obtained by dividing the hours of sunshine during the period by the number of days in the period.
Yield	1·70	4·5	1·8	8	
Loss	8·74	3·86	5·78	18·38	
Mean temperature, F.	52·9	39·6	55·2	mean 49·23	
Degree of humidity, mean	81·6	85·25	74	80·28	
S.H.D.	3·46	1·6	5·68	3·55	

It will be seen that although the temperature and hours of sunshine were greater, and the degree of humidity less in the growing period than in the replenishing period, the percentage of

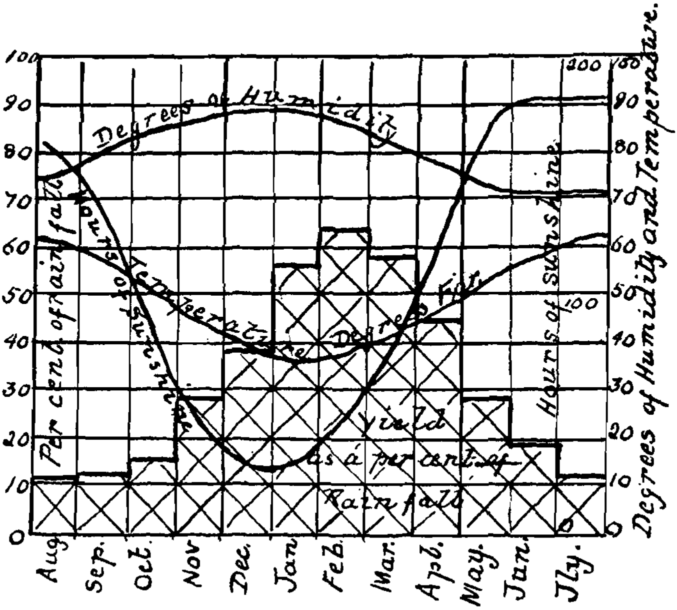

FIG. 15.

yield from rainfall was greater in the growing period than in the replenishing period, showing the effect of ground storage on yield. Fig. 15, which is a modification of the figure given in the "Proceedings of the Institute of Civil Engineers," quoted above, is a graphic representation of the table given above.

As an example of the variation in yield of a small area compared with a larger one under the same climatic conditions, the yields of the Talla basin and of the Gameshope basin are given below. The Talla basin comprises 6180 acres of hilly country, composed of Silurian greywacke and shale, the lower slopes of the hills are covered with a sheet of boulder clay, the upper and steeper slopes are covered with frost riven debris of greywacke, and shale, along with grit and sand. The Gameshope Burn is the main feeder of the Talla and drains an area of 3000 acres; the Gameshope Burn drains the upper portion of the Talla basin, and its basin is more permeable than the lower portion of the Talla basin; at the Talla reservoir the ground flow down the valley is practically intercepted by the impounding dam. The water year is divided into the following periods:—

Replenishing period, August to November—R.
Storage ,, December to March—S.
Growing ,, April to July—G.

	Talla.				Gameshope.			
	R.	S.	G.	Total.	R.	S.	G.	Total.
1906-07.								
Rain .	25·6	13·0	21·9	60·5	28·0	14·5	24·6	67·1
Yield .	21·2	19·2	16·3	56·7	22·2	19·0	16·5	57·7
Losses .	4·4	−6·2	5·6	3·8	5·8	−4·5	8·1	9·4
1907-08								
Rain .	25·3	22·7	14·3	62·3	27·9	25·5	15·7	69·1
Yield .	19·1	25·1	12·3	56·5	18·3	25·6	10·9	54·8
Losses .	6·2	−2·4	2·0	5·8	9·6	−0·1	4·8	14·3
1908-09								
Rain .	21·9	18·0	16·8	56·7	24·1	19·5	17·8	61·4
Yield .	16·6	19·8	15·2	51·6	16·1	19·3	13·9	49·3
Losses .	5·3	−1·8	1·6	5·1	8·0	0·2	3·9	12·1
1909-10								
Rain .	23·2	26·4	18·0	67·6	25·6	29·0	19·8	74·4
Yield .	18·3	28·2	10·6	57·1	18·2	22·6	7·8	48·6
Losses .	4·9	−1·8	7·4	10·5	7·4	6·4	12·0	25·8
1910-11								
Rain .	19·1	19·0	17·7	55·8	21·0	22·5	20·4	63·9
Yield .	16·1	21·4	13·5	51·0	13·4	18·0	9·6	41·0
Losses .	3·0	−2·4	4·2	4·8	7·6	4·5	10·8	22·9
1911-12								
Rain .	19·8	31·1	15·6	66·5	22·6	35·5	17·2	75·3
Yield .	16·5	28·1	13·3	57·9	14·7	38·6	11·8	65·1
Losses .	3·3	3·0	2·3	8·3	7·9	−3·1	5·4	10·2

The rainfall, surface yield, and losses are shown as inches on the hydrographical basin (*vide* "Proc. Inst. Civil Engineers," Vol. CXCIV.).

Taking the mean of the six years, we get—

	Talla.				Gameshope.			
	R.	S.	G.	Total.	R.	S.	G.	Total.
Rain .	22·5	21·7	17·4	61·6	24·9	24·4	19·25	68·55
Yield .	18·0	23·6	13·5	55·1	17·2	23·8	11·75	52·75
Losses .	4·5	−1·9	3·9	6·5	7·7	0·6	7·5	15·8

The mean of the six years shows that the surface yield from the Talla basin, considered as inches on the basin, was greater than that of the Gameshope basin, although the rainfall on the Talla basin was less than the rainfall on the Gameshope basin. The Talla basin, as a whole, is more impervious than the Gameshope basin, and at the Talla reservoir the ground flow down the valley is practically intercepted by the impounding dam, so that it seems reasonable to conjecture that the loss to ground water in the Gameshope basin was regained at the Talla basin. The mean annual evaporation from a water surface at the Talla reservoir for the six years under consideration was 16·6 inches, and this amount can be divided into—

5·1 inches during the replenishing period.
1·3 „ „ storage „
10·2 „ „ growing „

If the climatic losses bear any relation to the direct evaporation from a water surface, as may be reasonably expected, the effect of loss to ground storage in the replenishing period being recovered or partially recovered in the growing period is apparent.

Another example of a different character is that of the Burrator reservoir, Plymouth Water Works. The Burrator dam is built across the river Measey, which drains the western slope of Dartmoor. The elevation of the hydrographical basin draining into the reservoir varies from 700 feet to 1600 feet above Ordnance datum, and its area is 5360 acres. The whole area lies in granite formation; on the hills the rock lies close to the surface, but in the valleys the granite is decomposed, the decomposition often extending to depths of over 100 feet. The foundations of the dam are carried down to solid rock, so that the ground flow is practically intercepted. The decomposed granite is stated to be capable of holding 18 lb. of water per cubic foot in saturation. The statement below compares the rainfall, yield, and loss for the five years 1908 to 1912. The area of the basin draining into the reservoir is 4554 acres. The mean annual rainfall over the basin, being the mean of twenty-one calendar years, is 54·92 inches (*vide* "Proc. Inst. of Civil Engineers," Vol. CXC.). The water year is divided into—replenishing period, September to November; storage, December to April; and growing, May to August.

1. Year.		2. Replenishing.	3. Storage.	4. Growing.	5. Total.	6. Loss.	7. Evaporation from a Water Surface.
1907-08.	Rain .	16·81	24·27	14·70	55·78	—	—
,,	Yield .	14·00	34·11	11·05	57·16	− 1·38	17·55
1908-09.	Rain .	8·85	22·11	14·40	45·36	—	—
,,	Yield .	6·65	25·11	11·10	42·86	2·50	17·20
1909-10.	Rain .	16·70	30·70	19·42	66·82	—	—
,,	Yield .	13·52	39·90	14·00	67·42	− 1·40	16·59
1910-11.	Rain .	15·95	27·66	10·96	54·57	—	—
,,	Yield .	16·43	39·47	8·45	64·35	− 9·78	21·31
1911-12.	Rain .	16·30	41·50	28·15	85·95	—	—
,,	Yield .	9·27	52·64	21·10	83·03	2·92	17·31

Column 7 is the evaporation from a tank 6 feet square fixed at an elevation of 755 feet above Ordnance datum. As the geological formation is granite, the loss from deep seepage must be nil; and the depth and extent of decomposed granite must act as a large ground storage reservoir. It is also possible that percolation from the leet or old supply channel running across the basin augments the ground supply.

Large areas underlaid by permeable beds are not regarded favourably by engineers in search of sites for reservoirs, but if suitable sites for the construction of reservoirs in such areas are obtainable, and the impounding dam is carried down to the underlying impermeable stratum so as to intercept the ground flow, a water supply project may be developed with a reservoir of smaller capacity than would be required if the basin was impervious. Such a subterranean reservoir would be shielded from surface evaporation; and if in the higher reaches of the valleys of the basin the ground water plane of saturation is sufficiently below the ground surface, the loss by soil evaporation would be small.

40. A river basin under tropical conditions will now be considered. The Penner river, South India, drains the high lands of the Mysore plateau, and the Cuddapah and the Nellore districts of the Madras Presidency. The river falls from a level of 2500 feet above the level of the sea to the coastal plains of Nellore, and at Sangam some 50 miles from the sea, an anicut, or low dam, is built across the river to divert supplies coming down the river into an irrigation canal. The anicut is 7 feet in height, and is built on shallow well foundations sunk into the sandy bed of the river, so that the ground flow in the deep sandy bed of the river is not intercepted. The area of the hydrographic basin of the river above the anicut is 21,000 square miles, and its geological character consists, in the highlands of Mysore, of granitoid gneiss with a thin covering of soil, in the Cuddapah district of quartzites, shales, and limestone, and in the Nellore district of alluvium overlying quartz rock and schistose gneiss. There are no permeable beds of any great depth except the deep sandy bed of the river, and narrow valleys filled with talus and debris. The basin contains innumerable tanks, or small reservoirs, which intercept the supplies to the main stream so that the surface run off or yield at the Sangam is uncertain, yet when cyclonic storms sweep over the country the river comes down in alarming floods (*vide* "Proc. Inst. Civil Engineers," Vol. CXXXIV.). The basin lies in the zone of uncertain rainfall, and except for thunderstorms in April and May, the bulk of the rain is precipitated during the months of August to December. The months of April, May, and the early part of June are hot and extremely dry, the mean temperature over the basin being 90° F. in the shade. Temperatures of 110° F. in the shade have been registered at Cuddapah at the end of May. In the coastal districts of Nellore the sea breeze tempers the heat and increases the degree of humidity. During the rainy season the humidity is high, and the temperature averages 80° to 85° F. In the cold weather, January to March, the air is cold and dry, and the temperature averages 60° F. Owing to the numerous tanks in the basin the evaporation from water surfaces must be great.

The discharges at the Sangam anicut are taken from the river diagrams prepared by the Irrigation Department and may be accepted as reasonably accurate. The water year is divided into three periods: *Rains*, July to December inclusive; *Cold Weather*, January to March; *Hot Weather*, April to June. The statement below shows rainfall and surface yield at the Sangam anicut in inches on the catchment basin for the years 1898-1899 to 1904-1905:—

Year.	Periods.			Total.
	Rains.	Cold.	Hot.	
1898-99. Rainfall .	21·32	0	5·05	26·37
,, Yield .	2·40	0·063	0·046	2·51
,, Loss .	18·92	– 0·063	5·004	23·86
1899-1900. Rainfall .	14·16	0·02	4·31	18·49
,, Yield .	0·91	0·007	0·035	0·95
,, Loss .	13·25	0·014	4·275	17·54
1900-01. Rainfall .	17·83	2·23	4·01	24·08
,, Yield .	1·69	0·056	0·094	1·84
,, Loss .	16·15	2·174	3·916	22·24
1901-02. Rainfall .	17·56	0·42	5·04	23·02
,, Yield .	0·95	0·047	0·023	1·02
,, Loss .	10·611	0·373	5·017	22·00
1902-03. Rainfall .	23·96	1·17	6·23	31·36
,, Yield .	2·477	0·19	0·06	2·73
,, Loss .	21·483	0·98	6·17	28·63
1903-04. Rainfall .	37·55	0·49	3·66	41·70
,, Yield .	6·557	0·464	0·039	7·06
,, Loss .	30·993	0·026	3·621	34·64

Year.	Rains.	Cold.	Hot.	Total.
1904-05—				
Rainfall .	10·39	1·09	—	—
Yield .	0·313	0·004	Supply practically nil.	0·32
Loss .	10·077	1·086	—	—

Arranging the rainfall yield and loss in order of magnitude :—

Year.	Rainfall.	Yield.	Loss.
1904-05 .	Say 15	0·32	—
1899-1900 .	18·49	0·95	17·54
1901-02 .	23·02	1·02	22·00
1900-01 .	24·08	1·84	22·24
1898-99 .	26·37	2·51	23·86
1902-03 .	31·36	2·73	28·63
1903-04 .	41·70	7·06	34·64

It has already been pointed out (*vide* para. 18) that when the ground surface is completely dry soil evaporation is checked and considerably reduced, consequently the small losses observed in the years 1904-05 and 1899-1900 are due to the rainfall being not sufficient to completely damp the soil. Vegetation suffered, and transpiration and soil evaporation were less than what

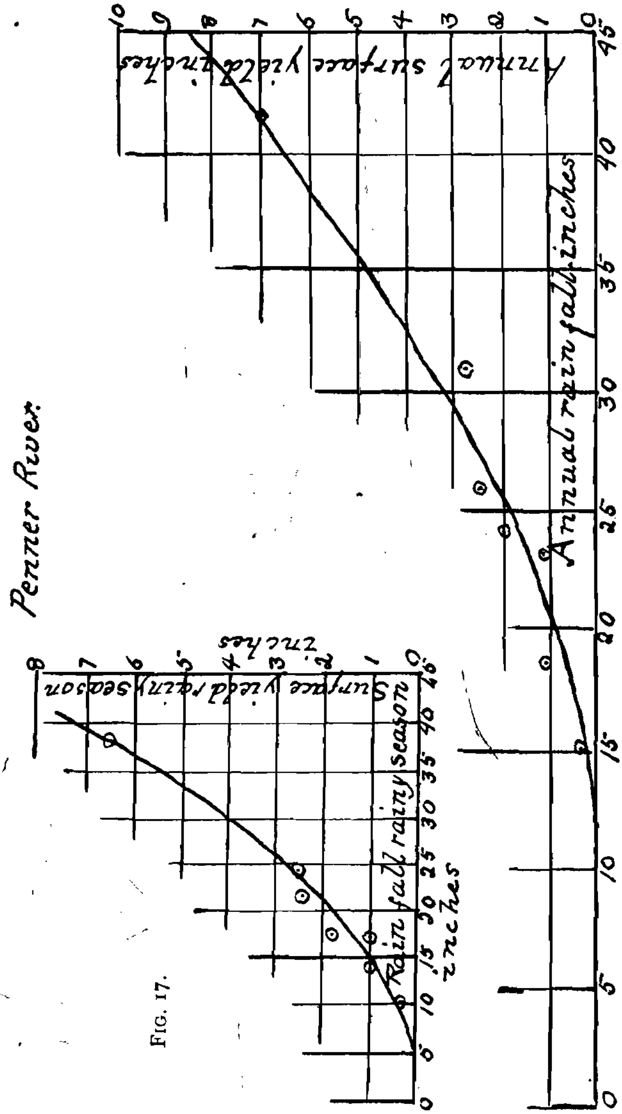

FIG. 16.

FIG. 17.

would have been expected from the climatic conditions, i.e. the temperature and humidity of the basin. The numerous tanks in the basin also received a scant supply, and the evaporation from water surfaces was also small. On the other hand, the loss of 34·64 inches in 1903-04 was due to the moist condition of the soil causing increased vegtation, and consequently greater loss from transpiration and soil evaporation. The tanks were full, and there were a greater number of puddles and streamlets, all contributing to a greater loss from evaporation from water surfaces than in other years. The ground water plane was also considerably raised. That the ground storage had some small effect on the yield is evident, as is shown by the yield of the cold weather of 1903-04 almost equalling the rainfall. No account is taken of the ground flow in the deep sandy bed of the river at the Sangam anicut, which appears as surface flow some 20 miles lower down the river. Owing to the small extent of permeable area the loss and gain from ground water is small, and it is possible to construct a curve of the annual yield that may be expected from the basin, due to the rain falling on it (*vide* Fig. 16). It will be also seen that the rainy season dominates the yield (*vide* Fig. 17).

Another tropical example is that of the catchment of the Helena river supplying the Mundaring reservoir, Western Australia. The Mundaring reservoir was constructed to supply Coolgardie with water. The hydrographical basin of the Helena river above the reservoir is 569 square miles in extent, and its geological character consists of crystalline rocks, the lower parts of the valleys being filled with a deposit of white clay, and most of the catchment area has a surface layer of ironstone gravel 1 to 3 feet in thickness, overlying decomposed granite; the solid granite is generally reached at a depth of about 20 feet from the surface. The whole watershed is timbered with jarrah, red gum, and wandoo, and covered with an undergrowth of Black Boys. The rainfall is spread over from May to November in light falls, averaging $\frac{1}{4}$ inch a day, and the main watercourses are stated not to begin to flow until 10 to 12 inches of rain have fallen, and stop almost immediately the rainy season ends. The evaporation from a water surface measured at the Perth Observatory from July, 1901, to June, 1902, was 65·79 inches ("Proc. Inst. Civil Engineers," Vol. CLXII.).

Comparing the surface yield from the Mundaring reservoir basin with that from two catchment basins below, and west of the dam, one 50 square miles in extent, and the other 10 square miles in extent, the Mundaring basin being 569 square miles (see Table).

The low surface yield of the Mundaring basin is stated to be due to the heavy vegetation, the porous surface overlying the solid rock, and the light and intermittent character of the rainfall.

Year.	Rainfall.	Yield.	Loss.	Remarks.
1899	27·2	0·225	27	Rainfall on the basin is the mean between Mundaring and York.
1900	33·2	1·167	32·033	
1901	25·0	0·170	24·83	
Catchment basin of 50 square miles west of the reservoir.				
1899	34·73	2·266	32·443	Rainfall on these two basins is the mean between Perth Gardens and Mundaring.
1900	40·91	7·435	33·475	
1901	35·80	3·602	32·198	
Catchment basin of 10 square miles west of the reservoir.				
1899	34·73	2·334	32·376	
1900	40·91	8·333	32·577	
1901	35·80	4·111	31·689	

The Mundaring dam is carried down to solid rock, and the ground flow or seepage under and through the dam is small. The catchment basins of 50 and 10 square miles are stated to have quicker shedding catchments, but their greater yield than that of the Mundaring basin is due to the greater rainfall on them. An inspection of the statement above shows the losses to be the same in all three basins.

An example of an arid basin is given below :—

Traka river. Karoo district of South Africa :—

Average	annual	rainfall,	8·67	inches.	Surface yield,	5·58	per cent.	of rainfall.
,,	,,	,,	8	,,	,,	1·88	,,	,,
,,	,,	,,	4·62	,,	,,	2·38	,,	,,
,,	,,	,,	6·63	,,	,,	5·43	,,	,,

The variations of yield are characteristic of South African catchment basins, and are due to the manner in which the rain falls; and the surface yield depends not on the annual or monthly rainfall, but on the individual falls. In certain Karoo areas the least rainfall producing a discharge ranges from 0·3 inches to 0·5 inches. An important factor is the state of the ground.

The Vaal river, with a hydrographical basin of 17,000 square miles, yields from 2 to 10 per cent. of the rain falling on it.

41. Few streams or rivers are so constant in their flow that if the full use of their yield is to be made for the purpose of a town water supply, or for an irrigation project, some storage will not be found necessary. A storage reservoir, therefore, is necessary to (1) balance the irregularities of flow during the seasons of a year; and (2) to hold the surplus water of "wet" years and make it available in the drier years that follow. As

an example, taking the case of the Penner river described in paragraph 40, and tabulating the data available, we get—

Year.	1898-99.	1899-1900.	1900-01.	1901-02.	1902-03.	1903-04.	1904-05.
Yield .	2·51	0·95	1·84	1·02	2·73	7·06	0·32

The total for the seven years is 16·43 inches on the basin, and the mean 2·347 inches on the basin. If we assume 2·347 as the "supply available," it is evident that the river will fail to give the required supply in 1899-1900, unless the rainfall in the years previous to 1898-99 was heavy, and the storage provided sufficient to carry forward a surplus to meet this deficiency. In the absence of this information, and using the data available, if we take the mean of the five years 1898-99 to 1902-03, omitting the year of heavy rainfall, 1903-04, the mean annual yield amounts to 1·58 inches, which we assume to be the "supply available." The storage required to balance the annual variations of yield can be obtained by adding yields and subtracting the demands (or "supply available"), and this is found to be 0·93 inch, which would be sufficient to balance the low supply in 1899-1900; but even if this reservoir was full at the end of 1903-04 it would not balance the low supply of the year 1904-05, and a reservoir capable of storing 1·25 inches on the basin would be necessary. In these assumptions the evaporation from the water surface of the reservoir has been neglected, and we have assumed that the yield is constant throughout the year, which is not the case.

The more correct method would be to divide the water year into periods of yield and demand, and in the case under consideration the first division would be to divide the year into two periods—six months rains and six months dry. A mass diagram is then prepared showing yield and demand. The mass curve is prepared by adding the half-yearly yields in succession forming the curve *abcd* . . . (*vide* Fig. 18). The ordinate y representing the total yield for the period denoted by the abscissa x. As the demand is usually uniform, the mass curve of demand can be represented by a straight line, as shown in the figure. So long as the demand curve does not exceed the yield curve, there will be no failure; therefore, by drawing a straight line from the origin so as just to keep within the mass curve of yield, the maximum demand that is possible can be obtained. The figure in this particular case shows the demand curve to amount to 1·58 inches on the basin in a year. The storage required can also be obtained directly from the diagram, and, as shown, amounts to a storage of 1·61 inches on the basin.

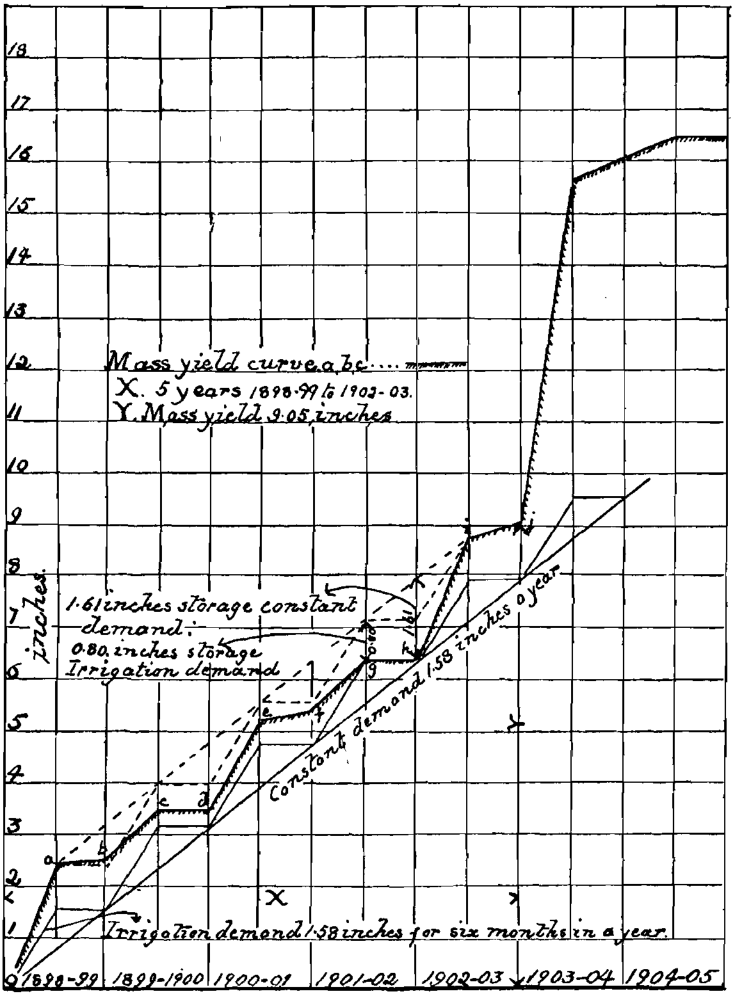

FIG. 18.

For it is obvious that if there was no storage the mass curve of demand would start again from *a*, and the deficits would be noted by the vertical lines from the new mass demand curve to the mass curve of yield. The longest of these lines will therefore denote the greatest amount of storage required. The mass curve of demand should again be verified from a mass curve of monthly or weekly yields for the critical dry years. In this particular case, the mass curves of supply and demand are drawn for the critical period at the end of the water year 1901-02, for the rainy season of 1902-03 (*vide* Fig. 19). It is seen that owing to the delay in the setting in of the rains, the supply just fails, indicating that the demand should be reduced, as no extra supply is obtainable. The yields of the rainy season 1902-03 are: July, 0·143; August, 0·105; September, 0·958; October, 0·590

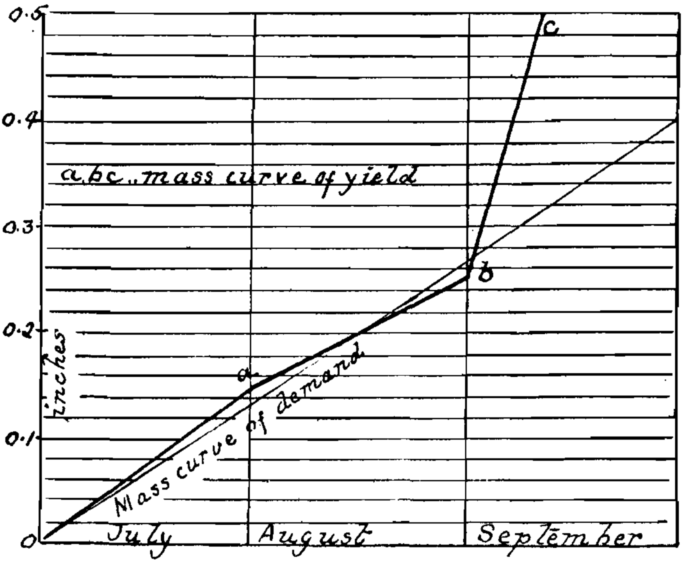

FIG. 19.

November, 0·481; and December, 0·20 inches on the basin. Assuming the mass demand curve to be 1·55 inches a year on the basin, the whole of this amount will not be the supply available, as a part will be lost by evaporation from the water surface of the reservoir. It is possible that in some regions of the earth the rainfall on the water surface of a reservoir may be equal to or greater than the evaporation from it, but in the case under consideration, the evaporation may amount to 75 inches a year. If the water surface of the reservoir capable of storing 1·61 inches on the hydrographic basin of the Penner be assumed as 20 square miles, and neglecting the actual rainfall on this area, the loss from evaporation a year would be equal to

$\frac{3}{42}$, or 0·071 inch on the Penner basin, and the available supply would be 1·55 – 0·07, or 1·48 inches on the hydrographical basin of the river.

For further accuracy, where the stream flow is irregular, it is advisable to compare the mass curve of weekly yields for the critical period with the mass demand curve. The attention of the reader is drawn to a paper read by Mr. Allen Hazen at the American Society of Civil Engineers, entitled "Probability Curves of Impounding Reservoirs" (Vol. XXXIX. of the Society's "Proceedings," 1913, pp. 1943 to 2044). The paper is worthy of perusal.

In the case of an irrigation project the demand will not be constant, and will depend on the nature of the crop grown. In the Nellore district the only crop that is irrigated to any large extent is rice, and the demand for a full six months' rice crop would be only during its season, that is, from June to December or July to January, according to the early or late arrival of the south-west monsoon. As a failure, or partial failure, in one year is not a serious matter, as it would be in the case of the water supply for a community, the demand may be assumed as 1·58 inches a year on the basin, required every six months. Under these conditions the required storage will be 0·82 inch on the basin (*vide* Fig. 18), and a smaller reservoir will meet the case. Assuming the loss by evaporation from this smaller reservoir to be 0·04 inch on the basin of the river, the available supply will be 1·58 – 0·04 = 1·54 inches on 21,000 square miles, or about 75,000 million cubic feet. Allowing 5 acres per million cubic feet, the supply would be sufficient to irrigate 375,000 acres of paddy.

In both cases, if the estimated cost of storage is found to be more than what may be considered financially possible, other mass curves of demand may be drawn, and a demand consistent with economy in storage obtained.

CHAPTER VIII.

FLOODS.

42. As rain falls on the earth a portion is immediately returned to the atmosphere, the remainder soaks into the earth, and as the surface of the particles forming the soil are clean, water has no difficulty in flowing over the surface of these particles into the sub-soil; with a lengthened rainfall the interspaces of the soil will become uniformly occupied with water and gas, and if the rate of rainfall is greater than that which can pass through the minute spaces of the soil in a unit of time, the water remains on the surface, or runs off into the nearest drainage channels. As floods depend on the amount of the rainfall that runs off the ground, it is evident that the greater the rainfall during any period of time over the amount of percolation into the soil during the same period the greater will be the run-off. Floods are therefore the result of rainfalls of great intensity, and their magnitude depends more on the intensity of the rainfall, that is, the rate at which the rain falls, rather than on the total amount of the rainfall.

The geological character of the country also influences the run-off; large areas and a great depth of sand would, unless the rainfall was so heavy as to completely saturate the sub-soil, give little run-off. Whereas, on the other hand, if the tract of country consists of bare impervious and unfissured rock, the whole rainfall discharged on it, less some small quantity carried off by evaporation, will run off the ground. In the case of cities and towns, the per cent. of rain running off built-on areas will be greater than that running off parks and garden areas.

The extent and general topography of a hydrographical basin will also influence the flood discharge of the main watercourse draining it. The form and length of the basin, the outlines of the principal valleys, the lengths and gradients of the minor watercourses, or feeders to the main stream, are important factors in determining the flood discharges that may be anticipated from rainfall on the basin. If the basin be long and narrow, the time required to discharge the rain falling on it will be longer than if the valley were semi-circular or fan-shaped, and the watercourses draining it converged to one common outlet. If there were depressions in the basin forming lakes, a part of the flow will accumulate in them, and the intensity of the flood at the outlet will be diminished. When the vegetation is dense and the basin wooded, the rainfall is retained and allowed to pass off slowly; and in tropical countries subject to heavy downpours of rain, forests and undergrowth on mountain and hillsides maintain the earth slopes, which absorb the rain and maintain a uniform flow in springs and rivers, instead of allowing the rain to scour away the soil and form floods disastrous to crops in the plains below.

43. In estimating the probable flood discharge that may be expected from an hydrological basin, a knowledge of all heavy *falls of rain on the basin, their intensities, and the causes pro*ducing them, is required. But it is necessary to point out that the degree of saturation of the basin has also to be considered, and this factor becomes more important the greater the area of the basin.

In a basin of large area a rainfall of great intensity but of short duration, after a period of drought, may produce a smaller flood than a rainfall of less intensity following on a period of long continued rainfall, when the soil and sub-soil are saturated, and rivulets, streams, and tributaries of the main water course draining the basin are already full. It is evident, therefore, that the conditions necessary to produce a maximum flood are a moderate rainfall for a long duration of time followed by a fall of great intensity for a short period of time.

44. It has been generally accepted that the intensity of rainfall on any area increases as the area diminishes, that is, in a locality under the same meteorological conditions a greater intensity of rainfall may be expected over an area of 5 square miles than over an area of 50 square miles. Very great intensities of rain or sudden cloud-bursts are, as a rule, usually produced by thunderstorms which extend over small areas, while the maximum intensities of twelve to twenty-four hours' duration occur during the long continued rainy or "wet" season. The flooding of streets, sewers, and railway cuttings usually occur in the summer, or during the seasons of thunderstorms; while in the case of rivers draining large areas, floods in them generally occur during the rainy season of the country they drain. Although it may be generally accepted that intensities of rain vary indirectly with the extent of the area over which it falls in any given storm or cyclone, there have been cases where

cyclonic storms have occurred giving heavy rain over very widespread areas. In the great flood of the 17th and 18th September, 1880, in Rohil Kand and adjacent districts in North India, an average of more than 10 inches in two days was recorded over the greater part of an area of not less than 10,000 square miles. On the 14th and 15th July, 1882, an average fall of 5 inches in twenty-four hours occurred over the greater part of the Central Provinces, south of the Nerbudda and Sone Valleys, comprising an area of 30,000 square miles. In the cyclone of November, 1903, which struck the Madras coast and spread inland, an average rainfall of 7·41 inches in twenty-four hours occurred over the basin of the Cheyar river, comprising an area of 3000 square miles. The great storm of 5th July, 1905, in America covered all the South Atlantic States, comprising an area of 200,000 square miles, resulting in an average maximum intensity of 2½ to 3 inches an hour. Summer rains have occasionally a widespread area; in the summer of 1903, 2½ inches of rain fell all over the London area in 24 hours, and in one or two places there was as much as 3 inches in twenty-four hours.

45. From the study of rainfall statistics for any lengthy period of time, it will be found that rainfalls of great intensity are very variable, but it should be possible to lay down the maximum intensity that is not likely to be exceeded once in 10, or 20, or 30, or . . . 100 years; the longer the period the greater the intensity of the rainfall. That is a greater intensity of rainfall may be expected to occur once in 100 years than once in thirty years, and decreasing the shorter the duration of the period. As an example, in India for a period of 100 years the highest recorded rainfall in a day of twenty-four hours was 35 inches, in the Bhagulpore division of Bengal (excluding Cherapunji and rainfall in the Assam hills). Other heavy recorded rainfalls during the same period were:—

Rohil Khand, 18th September, 1880—33·40 inches in twenty-four hours.

Madras, 31st October, 1846—20·58 inches in twenty-four hours.

Dorhaju in Sind, 4th August, 1866—20·00 inches in twenty-four hours.

Joongshais, 32·22 inches fell on the 5th and 6th August, of which 19·1 inches fell on the 5th.

In the great cyclonic storm which swept Gugerat in 1905, 30 inches of rain was measured in thirty hours at Sabramatti, of which 23·11 inches fell in twenty-four hours.

At the Kala Naddi aqueduct, Lower Ganges Canal, 17 inches *fell in one day, and 3 inches in the next.*

At Patna 15 inches fell in one day and 7 inches in the next.

At Kattiawar, with a mean annual rainfall of 27·70 inches, 23 inches was measured in eleven hours on 1st August, 1900.

At Calcutta the total rainfall for the week ending 25th September, 1900, was 40·35 inches, of which 14·53 inches fell on the 20th, and 10·83 inches on the 21st.

At Sholapur, 17 inches was recorded in twenty-four hours.

Comparing Lanowla, on the west coast of India, which receives the rains of the south-west monsoon, and little or no rain during the north-east monsoon, and Madras on the east coast, which receives the rains of the north-east monsoon, and only a few showers in the south-west monsoon, the table below shows records of falls of 10 inches in twenty-four hours and above :—

At Lanowla in—

1896.	Maximum	recorded	rainfall in	24 hours,	19·48	inches.
1900.	,,	,,	,,	,,	16·24	,,
1891.	,,	,,	,,	,,	14·51	,,
1894.	,,	,,	,,	,,	13·69	,,
1881.	,,	,,	,,	,,	12·88	,,
1907.	,,	,,	,,	,,	12·25	,,
1898.	,,	,,	,,	,,	12·10	,,
1912.	,,	,,	,,	,,	12·05	,,
1913.	,,	,,	,,	,,	11·45	,,
1887.	,,	,,	,,	,,	11·50	,,
1893.	,,	,,	,,	,,	11·34	,,
1882.	,,	,,	,,	,,	11·02	,,
1885.	,,	,,	,,	,,	10·85	,,
1892.	,,	,,	,,	,,	10·39	,,
1880.	,,	,,	,,	,,	10·81	,,
1879.	,,	,,	,,	,,	10·50	,,

At Madras :—

1846.	Maximum	rainfall	recorded in	24 hours,	20·58	,,
1857.	,,	,,	,,	,,	18·04	,,
1872.	,,	,,	,,	,,	13·01	,,
1827.	,,	,,	,,	,,	12·00	,,
1851.	,,	,,	,,	,,	11·45	,,
1820.	,,	,,	,,	,,	11·12	,,
1819.	,,	,,	,,	,,	10·00	,,

It is possible that more records of 10 inches in twenty-four hours exist for Madras.

Taking into consideration the meteorological conditions prevailing in India, it may be reasonably anticipated that rainfalls of 10 inches in twenty-four hours are frequent, and that rainfall intensities of 20 inches in twenty-four hours may be expected to occur in a period of 100 years, and that this maximum is liable to be exceeded.

Regarding excessive falls of rain in India, Blandford states that they are always the result of cyclonic storms which sweep over the country, in which the barometer is not greatly depressed. Another noteworthy point is that they frequently occur in years of partial drought, as if in such seasons the whole energy of rain formation were concentrated in the storms to the deprivation of parts of the country not reached by them. Also, in countries, more particularly in the tropics, where the rain falls only in certain periods of the year, as in India, the rate of fall is consequently heavier than in countries where the rainfall is more uniformly distributed throughout the year, and the rain is less penetrating in proportion to its quantity, so that instead of feeding springs, and streams, and nourishing an absorbent cushion of green herbage, the greater part flows off the surface into the dry beds of its watercourses, causing temporary torrents. In uncultivated tracts where fires have destroyed and withered the grass and bushy undergrowth, and have laid bare the soil and hardened its surface, this action is enhanced, and while all perennial water supplies which depend on the absorbed rain are greatly reduced or altogether suppressed, a rainfall which, if husbanded by nature and art, would suffice for agricultural and domestic requirements of the population, is thrown into watercourses and rivers, and not only wasted and lost for any useful purpose, but by producing floods becomes an agent of destruction. Much more, therefore, than in temperate climates is it incumbent on us to safeguard such provident arrangements as nature has furnished for the purpose ("Climate and Weather of India, Burmah, and Ceylon").

Observations of shorter durations of rainfall go to substantiate the rule that a greater intensity of rainfall may be expected to occur once in a long period of time than once in a comparatively shorter period. If for any locality a curve were drawn in which the abscissa represented the rate of fall in inches per hour, and the ordinate its frequency, in any long period of time, and if such a curve were a true hyperbola, this would indicate that the frequency of a fall of a given amount is inversely as its quantity, or the rate of fall multiplied by its relative frequency would be a constant.

46. The intensity of rainfall also varies with the duration of a heavy fall. Rainfalls of short duration are more frequent and of greater intensity than those over longer intervals of time, or, in other words, the rate of rainfall increases as the duration of the downpour diminishes. One of the principal sources of error in estimating the flood discharge from hydrographical basins of small areas, or from built-up areas as in cities and towns, is the measurements of the intensities of the rainfall for any short period of time, and for such purposes automatic recording rain-gauges are essential. Thus, in town drainage schemes it is necessary, in the first instance, to decide on the greatest rainfall to be anticipated in one hour, and often for shorter periods. In the case of irrigation works and railways, provision may often have to be made for the greatest rainfall that may occur in half an hour. "British Rainfall" gives the following records of falls of great intensity for a period of forty-nine years—

If t be the duration of the fall in minutes;

R the actual recorded fall in inches;

I the intensity of the fall, or rate of that fall in inches per hour.

For remarkable occurrences :—

t . .	10	20	30	40	50	60
R .	0·65	1·06	1·35	1·54	1·67	1·75
I . .	3·9	3·18	2·70	2·31	2·00	1·75

For very rare cases :—

t . .	10	20	30	40	50	60
R .	1	1·58	2	2·26	2·42	2·5
I . .	6	4·74	4	3·39	2·90	2·5

Special cases :—

t	5	15	30	45	60
R	1·25	1·46	2·90	3·42	3·63
I	15	5·84	5·80	4·56	3·63

Mr. G. T. Symons has stated that in the storm of 1878 in London the intensity of I for a short interval of time was as much as 12 ("Proc. Inst. Civil Engineers," Vol. CXXIX., p. 114). In the Streatham and Baldwin districts in 1914, 2·84 inches fell in 2·80 hours, the greater part of which fell in one hour. On 16th June, 1917, 4·70 inches fell in two hours at Campden Hill, On the 25th August, 1912, 8 inches fell in less than twenty-four hours at Norwich. In May, 1920, 4·72 inches fell in two and a half hours at Hallington, near Louth.

In America.—In California during the period 1871 to 1898 the maximum recorded rainfall was 8·67 inches in one hour; while there were numerous records of falls of 3 inches to 4 inches in an hour. The following statement shows the maximum observed values of I for various durations of time t at Chestnut Hill, Boston, Mass., U.S.A., in a period of fifteen years :—

t .	5	10	15	20	30	45	60	80	100	120	150	180
I .	7·4	4·85	3·82	3·31	2·65	2	1·65	1·35	1·18	1·02	0·87	0·79

At Chicago, Illinois, U.S.A., the following maximum intensities were observed from 1889 to 1897 :—

t . .	5	22	55	60
I . .	6·8	3·5	1·4	1·2

Prussian observations from 1891 to 1893 give the following maximum intensities out of 1236 cases :—

$t = 1$ to 5. $\quad$ I $= 8·22$.
$t = 6$ to 15. $\quad$ I $= 4·98$.

For heavy falls of rain, the duration of which extends to three hours, I $= 0·66$.

At Pretoria, South Africa, with an annual rainfall of 26·06 inches, the following maximum intensities have been observed :—

Duration of fall in hours . . .	$\frac{1}{4}$	$1\frac{3}{4}$	2	6	$11\frac{1}{2}$
Rate of fall (inches per hour or I) .	3·40	1·19	1·78	0·8	0·4

The greater part of the precipitation takes place during a few heavy storms. For small areas falls at the rate of 4 inches an hour for a few minutes may be expected. In the flood of January, 1909, 4·83 inches fell in six hours, of which 3·56 inches fell in two hours.

At Bloemfontein, with an annual rainfall of 23·44 inches, rainfalls of 4 to 5 inches an hour were experienced on the ridge west of the town during the flood of 17th January, 1904. At

Belgravia, Johannesburg, the maximum intensity recorded was 3 inches an hour on 18th November, 1904. Sporadic falls of ½ inch in ten minutes have been recorded in the Transvaal.

In Australia.—Observations at Sydney for the period 1869 to 1901 show the following results :—

Average annual rainfall, 50 inches.
Maximum annual rainfall, 82·81 inches in 1859 and 81·42 inches in 1890.
Maximum fall in twenty-four hours, 20·41 inches fell in 20·30 hours, of which 5·40 inches fell in two hours, 15th October, 1884.

In Central Queensland, with a mean rainfall of 40·63 inches for the period 1871 to 1903. At Rockhampton, 24 inches was recorded in twenty-four hours in 1875, and 17 inches in twenty-four hours in 1888, due to cyclones.

Mr. Chamier states that in the temperate zones of Australia one-quarter the mean annual rainfall has been known to fall in twenty-four hours, and one-quarter the maximum of twenty-four hours to fall in one hour (" Proc. Inst. Civil Engineers," Vol. CXXXIV., p. 315).

At Hong-Kong the rainy or wet season lasts from May to September, and the dry season from October to April. The rains in the first month of the wet season are due to the change in the monsoon, and give light, well-distributed rain, but thunderstorms which are prevalent at this time of the year are generally accompanied by heavy rain. The rains of August and September are due to typhoons. In the period 1884 to 1913, the maximum annual rainfall recorded at the observatory was 119·72 in 1889, and the minimum 45·83 inches in 1895.

The maximum daily intensity recorded was 33·11 inches in thirty-eight hours, from 3 A.M. of 29th May, to 5 P.M., 30th May, 1889. The maximum hourly recorded fall was 3·4 inches in one hour.

Rainless localities are often subject to sudden downpours of rain. At Cairo, with an average annual rainfall of 1 inch, the maximum annual rainfall recorded being 1·96 inches. In the period of eleven years ending 1915, there were eight occasions when the rainfall exceeded 0·39 inch in twenty-four hours. The maximum recorded fall in twenty-four hours was 1 inch.

In the Lower Nile Delta the maximum recorded rainfall is 3 inches in twenty-four hours, on the 7th October, 1876.

Turning to India, the following are recorded intensities of rainfall :—

Calcutta—t . .	20	60	120	180
R . .	3·00	4	7·50	12
I . .	9·00	4	3·75	34
Bombay—t . .	60	120	960	1440
R . .	4·2	5·5	12·25	14·53
I . .	4·2	2·75	0·77	0·6

Maximum recorded, 40·35 inches from 20th to 25th September, 1900, of which 14·53 fell in twenty-four hours.

Sholapur—t . . .	420
R . . .	10
I . . .	1·43

Baroach, 8 inches was recorded in two hours. I = 4.

In Gugerat, with a mean annual rainfall of 30 inches, maximum recorded rainfalls were 23·11 inches in twenty-four hours, and 30 inches in thirty hours—I = 1. In Kathiawar, with a mean annual rainfall of 27·70 inches on 1st August, 1900, 23 inches was gauged in eleven hours—I = 2·1 nearly. In the rainless tracts of the Punjab 8 inches have been recorded in eight hours. Below the Himalayas, in 1908, a year of heavy rainfall, the following intensities were recorded :—

t .	5	20
I .	5·4	4·8

Madras, *21st October, 1846 :*	*20·58 inches recorded in*	24 hours.	I = 0·816.
,, ,, ,,	17 ,, ,,	12 ,,	I = 1·42.
,, 20th November, 1856 :	6·22 ,, ,,	5 ,,	I = 1·24.
,, 24th October, 1874 :	4·95 ,, ,,	3 ,,	I = 1·65.
,, May, 1861 :	1·6 ,, ,,	40 mins.	I = 2·40.
,, September, 1860 :	1·2 ,, ,,	15 ,,	I = 4·80.
,, October, 1893 :	1 ,, ,,	16 ,,	I = 4 nearly.
,, A single record :	2 ,, ,,	18 ,,	I = 6·66.

Tabulating the results :—

t . .	15	16	40	180	720	1440
I . .	4·80	4	2·4	1·65	1·42	0·82

Blandford states that falls of 3 to 4 inches an hour are not rare in India, and such falls last from two to three hours in succession ("Climate and Weather of India, Burmah, and Ceylon").

Plotting these rainfalls, together with other rainfalls of short duration which are not recorded above, where t, the abscissa, denotes the duration of the fall in minutes, and R, the ordinate, denotes the actual amount of the fall in inches (*vide* Fig. 20), we find that up to a duration of time t of 1440 minutes, or twenty-four hours, a simple parabolic curve $R^2 = \frac{1}{4}t$ gives heavy rainfalls that are likely to occur over the greater part of India, except the hills. That is, if t denotes the duration of a heavy fall in minutes, and R the amount of that fall in inches,

$$R = \frac{1}{2}\sqrt{t}.$$

If I_t denotes the intensity of that fall in inches an hour, that is, if the rain continued to fall at the same rate for sixty minutes,

$$I_t = \frac{1}{2}\sqrt{t} \times \frac{60}{t} = \frac{30}{\sqrt{t}}.$$

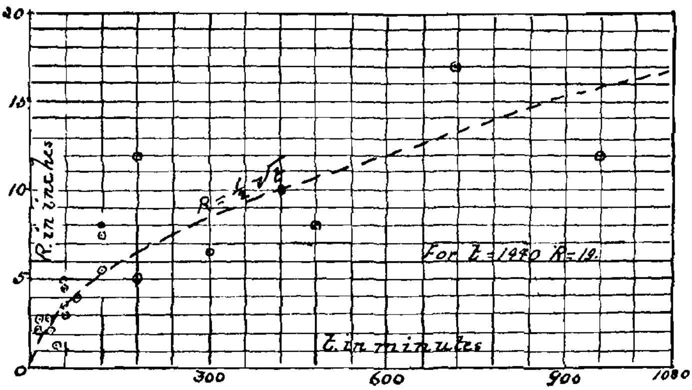

FIG. 20.

These intensities may be exceeded in a long period of years. Sherman's maxima intensities are given by the equation—

$$I_t = \frac{38 \cdot 64}{t^{0 \cdot 687}}.$$

Professor Talbot proposes two equations for the United States :—

$$I_t = \frac{360}{30 + t},$$

which gives intensities not likely to be exceeded more than two or three times in a century, and

$$I_t = \frac{105}{}$$

which gives intensities likely to be exceeded every two or three years.

For British rainfall, Parker (" Control of Water ") gives the equation

$$I_t = \frac{240}{30 + t}$$

for very rare occurrences, and

$$I_t = \frac{168}{30 + t}$$

for remarkable cases.

47. The quantity of water which will accumulate in a given time at the outlet of the watercourse draining a hydrographical basin depends among other things on—

(1) The area and shape of the basin above the outlet.

(2) Nature and surface of the basin. As has been already pointed out, the geological character of the basin will largely influence the run-off. Also, depressions or lakes in the basin acting as flood moderators will reduce the intensity of the run-off. Large areas of ploughed land will increase the retentive power of the soil; while, on the other hand, furrows, ditches, roads, and land drainage will greatly increase the amount and intensity of the run-off. Thus the opening out and developing of a country by making roads and other ways, the ditches and drains of which deliver the water to the watercourses more rapidly than heretofore, the drainage of land, the clearing of drainage courses, and streams of obstruction, may lead to greater floods down the main watercourses of a country than were formerly experienced. In the case of towns the extent of impermeable area such as roofs, pavements, and impermeable roads will largely influence the intensity of the run-off.

(3) The inclination of the surface of the ground is also a factor which will influence the run-off; and the resulting flood at the outlet will depend very considerably on the gradients of the watercourses carrying the freshets to the outlet. Apart from the magnitude of the flood discharge, the height to which the flood water will rise will depend on the gradients of the tributaries compared with that of the main stream. The combination of steep gradients in the former with flat slopes in the latter is very favourable to high floods.

(4) The degree of saturation of the ground, which becomes more important the greater the area of the basin.

(5) The duration of the rainfall, and the greatest intensity at which it falls for any period of time. The former will influence

the degree of saturation of the soil, and on the latter will depend the magnitude of the flood discharge.

48. In estimating the probable flood discharge from an hydrographical basin, it must be assumed that the rainfall is general over the whole extent of the basin simultaneously; also, that the rainfall is of sufficient duration to allow the flood water from all parts of the basin to reach the outlet. The area may be so large that it may take twenty-four hours or longer before the freshets from the boundaries of the basin can reach the outlet; in such cases it is only necessary to consider the intensities or rates of fall for twenty-four hours, or even forty-eight hours. On the other hand, if the basin be small and the tributaries all converge to the outlet, it may be necessary to consider the maximum intensities of one hour, or a shorter period of time. The relative direction and velocities of the storms or cyclones which cause heavy and widespread rainfall to that of the main stream draining the basin have also to be taken into consideration.

The general formula for the flood discharge from a hydrographical basin must be of the form

$$D = f(A \,.\, I_t \,.\, p)$$

where A is the area of the basin.

I_t the observed maximum intensity of rainfall for any period of time t required to concentrate the flood water, from every part of the basin, at the outlet;

p is the fraction of the rainfall which runs off the ground surface, which depends on the nature of the catchment, and degree of saturation of the soil and sub-soil.

For the purpose of calculating the greatest flood discharge to be provided for in connection with any hydrographical basin, an approximate knowledge of the maximum rainfall that is likely to occur during the time t is required. The value of t depends on the shape of the basin, chiefly on its greatest length, and is difficult to determine. Where systematic surveys of river basins are undertaken it should be possible to delineate the nature of the basin, and the gradients of its main watercourses, and from the information so obtained to deduce values for t. Where such surveys do not exist recourse must be made to scattered observations. Mr. Chamier states that under average conditions the velocities in watercourses range from 2 to 4 miles an hour, and the time taken to flow off the ground depends on the nature and inclination of the ground surface; on grass downs with moderate slopes the velocity of flow off the ground will be ½ mile an hour, and on steep declivities 1 mile per hour ("Proc.

Inst. Civil Engineers," Vol. CXXIV.). The velocity of the flood wave down the Papaghni river, South India, was 7 miles an hour; the river falling from 3000 feet above sea-level to 450 feet above sea-level in a distance of 90 miles. In the flood of 1903 the velocity of the flood wave down the Penner river, Southern India, was 5·53 miles an hour in a distance of 83 miles. The gradient of this reach of the river averaging 3·31 feet per mile. In the floods of 1907 in the Sacramento and San Joaquin Valleys, the rate of travel of the flood wave was from 4 to 9 miles an hour. Prussian observations from 1891 to 1893 show that for town areas the flood water takes three and a half times as long to reach the drains as to fall.

The method of estimating t also requires a certain amount of judgment, and it is possible by omitting the contribution of isolated areas to obtain a smaller value of t and a greater value of I_t. It is evident that for large areas the greatest rainfalls in twenty-four hours, or for a longer period of time, need only be considered. It will not affect the result whether the rain falls at the same rate in twenty-four hours or in heavy intermittent showers during the same period, assuming that the ground is saturated or nearly so from previous rainfall.

In estimating p, or the fraction of the rainfall which runs off the ground, the conditions most conducive to surface drainage must be considered. In countries where winter storms are prevalent, the ground is often frozen and thereby rendered almost impervious, so that it is usual to assume two-thirds, or the greater proportion of the rainfall, as flowing off the ground. In temperate climates, and more so in tropical climates, the geological character of the country largely influences the value of p. In all cases the greatest previous saturation which the rainfall and climate permit should be allowed for. Generally, the value of p varies from one-third to three-quarters. A fair value for wooded slopes and compact surfaces would be 0·5 to 0·6. For bare unfissured rock p may be as much as 0·8 to 0·9; and the same value may be assumed for impervious built-on areas. For towns which, in addition to built-on areas, include parks and roads p may be taken as 0·66.

49. Various curves have been devised for calculating the maximum flood discharges from hydrographical basins. The assumption being that river basins increase regularly in area, and have physical features as to slope and nature of soil, etc., all tending in the same degree to discharge the rain falling on them. Such, however, are the diversities of the physical features of natural basins, and the distribution of rainfall on them, that

a search for basins possessing exactly similar characteristics would probably be a vain one.

Col. Dickens' formula, which is largely used in North India, is stated to be applicable to an average rainfall of 36 inches a year, and to hold approximately for a rainfall of from 24 to 50 inches a year. It is based on the following assumptions :—

(1) Over 8 acres the precipitation may be as much as a rate of 4 inches an hour.

(2) Sir P. Cautley allowed $\frac{1}{2}$ inch an hour run-off from small basins which he assumed applied exactly to 50 square miles.

(3) The Damuda flood discharge was at a rate equivalent to a run-off of $\frac{1}{8}$ inch an hour from a catchment area of 7000 square miles.

(4) The Sone flood discharge from an area of 27,000 square miles was at the rate of $\frac{1}{10}$ inch an hour on the basin.

Tabulating the results :—

1.	2.	3.	4.	5.
Drainage Area.	Fourth Root of Drainage Area.	Rainfall Drained Off. Inches Per Hour.	Product of Columns 2 and 3.	Remarks.
$\frac{1}{80}$ square mile	$\frac{1}{3}$	4	1·33	
50 square miles. . .	2·5	$\frac{1}{2}$	1·25	Mean = 1·25
7000 "	9	$\frac{1}{8}$	1·13	$= \frac{5}{4}$.
27,000 "	13	$\frac{1}{10}$	1·30	

Or the rainfall drained off represented as inches per hour is inversely as the fourth root of the area of the basin.

If M = the area of the basin in square miles,

$$M^{\frac{1}{4}} \times \text{inches per hour drained off} = \frac{5}{4}.$$

$$\therefore \text{Inches drained off per hour} = \frac{5}{4M^{\frac{1}{4}}}.$$

If D = the resulting discharge in cubic feet per second, or "cusecs,"

$$D = 806M^{\frac{3}{4}}.$$

Dickens' formula, as it now stands, is $D = 825M^{\frac{3}{4}}$ (*vide* "Professional Papers, Indian Engineering," Vol. II., 1865). The formula is stated by Col. Dickens to be considered only a rough approximation, Col. Ryves' formula with the same symbols as above is

$$D = CM^{\frac{2}{3}}.$$

where $C = 450$ for areas within 15 miles of the coast.
$C = 563$ „ „ 15 to 100 miles of the coast.
$C = 675$ for limited areas near the hills.

The constants are for the Madras Presidency.

Mr. Fanning, in his "Hydrology and Water Supply," states that from recorded measurements of American streams which he plotted, he obtained the formula

$$D = 200M^{\frac{5}{6}}.$$

Mr. Chamier's formula, using the same symbols, is

$$D = 640R \, . \, C \, . \, M^{\frac{3}{4}}.$$

R = the average rate of greatest rainfall anticipated in inches per hour for such duration as will allow of the flood water flowing to the outlet from the farthest extremity of the basin, which corresponds to I_t in paragraph 48.

C = a co-efficient of surface discharge, giving the proportion of rainfall that may be expected to flow off the surface which corresponds to p in paragraph 48 (see Chamier on "Culverts and Flood Openings," "Proc. Inst. Civil Engineers," Vol. CXXXIV.).

Mr. James Craig divides the basin into triangles having their apexes coinciding with the outlet, and calling 2B in miles the length of the base and L in miles, the distance from its middle point to the outlet, he obtains for the area in square feet of the unobstructed flood section of the river at the point of discharge

$$A = 184 \times \Sigma \left(B \log \frac{8L^2}{B} \right)$$

where A is the area in square feet ("Proc. Inst. Civil Engineers," Vol. LXXX.).

It has been customary in the Madras Presidency in the investigation for the restoration of tanks, to assume, in the absence of more reliable data, that the difference between the rainfall and the corresponding run-off for any heavy fall of rain, over a standard area of 5 square miles, would probably be nil. The considerations which led to the adoption of this area were that so many of the irrigation tanks have catchment basins of about that area, and it was considered that by its adoption the risk of error from underestimating the rainfall in dealing with the generality of works would be avoided; and, secondly, that it was extremely probable that a maximum rainfall might extend over an area of this size. The considerations which led to neglecting the difference between the rainfall and the corresponding drainage over the standard area were: (1) Because in the case of heavy falls of rain, when this amounts to several inches, absorption is relatively small: 5 inches of rain distributed over twenty days might produce no drainage other than sub-soil, whereas of 5 inches of rain in one hour probably 95 per cent. would flow off the surface; (2) because data are wanting, and much closer approximations than those possible at present must be made before it would be prudent in the generality of cases to introduce coefficients of reduction. Any formula to be fairly reliable must take into account the maximum rainfall, time of its duration, the slope, and the nature of the country drained.

General Mullins, R.E., sometime Chief Engineer for Irrigation to the Government of Madras, laid down the following rules for obtaining the values of C in Dickens' and in Ryves' formulæ, based on the above remarks, viz., that the drainage from a standard area of 5 square miles would be equal to that of a heavy fall of rain on it.

If x be the mean of the maximum recorded rainfalls in twenty-four hours over any hydrographical basin,

$$\text{C in Dickens' formula} = 40x.$$
$$\text{C in Ryves' formula} = 46x.$$

which, he stated, in the absence of more accurate data might be accepted as approximate coefficients in the two formulæ. Provided the basins are moderately flat, and are to a certain extent pervious and cultivated, the values he stated would not hold good for steep impervious basins. For the drainage schemes of the Godavery delta, where the rainfall due to the cyclonic storms of the north-east monsoon frequently amounts to 10 inches in twenty-four hours; for areas of over 5 square miles General Mullins used Ryves' formula $D = 460M^{\frac{2}{3}}$ in designing the delta drainage. It is obvious that $D = 460M^{\frac{2}{3}}$ is equivalent to a run-off of 10 inches in twenty-four hours from a standard area of 5 square miles.

50. It has been stated (par. 48) that the general formula for the flood discharge from a hydrographical basin must be of the form

$$D = f(AI_tp).$$

If dA be a unit area;

t be the time it takes a freshet or the rainfall running off dA to reach the outlet, then in order to prevent accumulation of water at the outlet, the discharge at the outlet must be equal to the run-off from dA during the time t.

If I_t be the maximum intensity of rainfall corresponding to the duration of fall t (par. 46).

The discharge at the outlet for any short period of time from the unit area of the basin will be

$$p \, . \, dA \, . \, I_t dt$$

if the intensity of rainfall is confined to the area dA; but as stated in paragraph 46, in estimating the probable flood discharge from a hydrographical basin it is assumed that the rainfall is general over the whole extent of the basin, and of sufficient duration to allow flood water from all parts of the basin to reach the outlet. These conditions will probably obtain in catchments of moderate area, and where the length of the main watercourse does not exceed 40 or 50 miles, as in larger areas the whole basin is never completely saturated, and the intensity of rainfall per unit area may vary largely. Generally, it may be stated that as dA increases in area, t will increase in value the amount depending on the shape of the basin; and I_t will diminish in value. The problem is also complicated in large areas by the greatest intensity of rainfall being on areas near the outlet, or on areas distant from the outlet. The value to be assumed for t will not therefore necessarily be the time for the flood water from the extreme limits of the basin to reach the outlet, although it is generally assumed as such. The time of concentration depends on the quantity of water already on the area, size of channels conveying the flood water to the outlet, and the amount of submersion that is permissible. As an example, in the rice-bearing deltas of South India the paddy crop, when fully grown and about to mature, can endure submersion for six days without suffering any considerable damage, consequently General Mullins, R.E., in laying down rules for the drainage of the delta areas of the Godavery and Kistna rivers, which are subject to heavy cyclonic rainfalls, amounting frequently to 10 inches in twenty-four hours during the north-east monsoon, assumed a rainfall of 10 inches in twenty-four hours for one day and 2 inches for the remaining five days, or 12 inches in all, to be passed off in six days, or at the rate of 2 inches in twenty-four hours from areas up to 5 square miles. For larger areas he used Ryves' formula

$D = 460M^{\frac{3}{4}}$, and designed his drains to carry one-sixth of the resultant discharge.

51. The causes producing floods require careful study. In the case of catchments of small areas, thunderstorms, or cloud bursts may produce floods at any time of the year, whereas in the case of rivers possessing basins of large area, floods are generally expected during the rainy or "wet" season of the year, and it is possible to predict the months in which floods may be expected. In India heavy falls of rain over a large area of the country occur during cyclones or cyclonic storms, and their frequency at any given place is likely to vary with the liability of that place to come within the track of such cyclones.

In the North of India extending from Bengal nearly across the peninsula is a broad band in which the south-west monsoon is more or less abundant, regular, and certain. The cyclonic storms of the south-west or summer monsoon, which most frequently traverse India in a west-north-west direction from the Circar and Orissa coasts, usually traverse this region, and in their passage westwards are accompanied by heavy rain, and falls of great intensity have occurred in this belt of maximum storm frequency. The Satpura range of hills, which lies in this belt, is notoriously subject to heavy falls, producing floods in the Tapti and Nerbudda rivers. The extent of country simultaneously affected by these heavy rains is sometimes very great, usually some thousands of square miles in extent. The central part of India, including the Deccan and Hyderabad, are less frequently visited by cyclonic storms. In September the south-west monsoon begins to decline, but frequently isolated falls of considerable intensity occur in the Ceded districts of the Madras Presidency. On the east coast the monsoon begins to recurve in October, and a copious rainfall is discharged over the hitherto scantily watered plains of the Carnatic. The rains of the Carnatic last till December, the seat of their chief prevalence moving gradually southwards with the declining year. October and November are generally the months in which the cyclonic storms strike the Coromandel Coast, and sweep inland with diminishing intensity.

52. The damage caused by floods is often very considerable. In the storm of July, 1905, in Gujarat, India, the damage in the town of Ahmedabad in the grain and the sugar stores was estimated at £33,000. In March, 1907, floods in the Sacramento and San Joaquin Valleys resulted in the inundation of 300,000 acres of crops, besides destruction to the railway in many places. An earthen dam across the south branch of the little Commangh

river, Pennsylvania, was breached on the 31st May, 1889, by the water overtopping the dam by 20 inches, and cutting through the bank in two and a half hours; the resulting flood down the valley caused a loss of more than 2000 lives and a million dollars' worth of property. To come nearer home, the flood at Louth was caused by the exceptionally heavy rain on the Wolds. The whole of the rainfall fell in two and a half hours, and during that period—

1·43	inches	were	measured at	Louth.
4·72	,,	,,	,,	Hallington.
4·59	,,	,,	,,	Welton-le-Wold.

The river Lud, normally running 5 yards wide and 1 foot deep, in half an hour after the rains was swollen to an average width of 150 yards and a depth of 10 feet. The velocity of the flood water being estimated at 15 miles per hour. The catchment of the Lud above Louth is estimated at about 20,000 acres, the nature of the catchment being chalk hills cultivated with large farms. The flood is ascribed to be due to the excessive rainfall at Little Welton, situated between Elkington and Welton-le-Wold, where the intensity of rainfall was estimated to be as much as 8 inches an hour. The flood at Louth exemplifies the fact that a combination of steep slopes of tributaries with a flat slope of the main stream is very favourable to high floods.

The effect of floods on public health often result in rheumatism, chills, and colds, due to damp soil and dwellings. Disease may be propagated along with the water in the sub-soil. Typhoid has been known to break out three to six weeks after an inundation, and there may be diseases due to shock, fright, and physical excitement. Injuries may be caused to health by defective nutrition due to absence of communication with markets, or destruction of factories, and consequent unemployment, and to overcrowding, owing to the destruction of homes. On the other hand, particularly in India, storms accompanied by floods often cleanse a town of an epidemic. The evils of flooding can be remedied by collecting basins to retard the arrival of large bodies of water in the principal waterways, and storing the water for the benefit and use of man, and improving the flowing power of streams and natural drainage courses, and cleansing them of obstructions. The first essential to effective drainage is that the flood water must have a free, outward, and uninterrupted flow, and the river draining the hydrographical basin under consideration must be dealt with as a whole. Even in this country large areas of land are subject to inundation, and if their drainage courses were satisfactorily and comprehensively dealt with, a considerable extent of valuable land would be added to the country.

The frequency of great floods, and the amount of money that can be spent in preventing or ameliorating inundations due to them, so as to be commensurate with the resulting advantages, is one of the most difficult problems which confronts the civil engineer.

CHAPTER IX.

WELLS AS A SOURCE OF WATER SUPPLY.

53. It has been said that "Life is an aquatic phenomenon," that is, every living thing, whether animal or vegetable, depends on water for its life. Without water there would be no life. All places where human beings congregate and dwell are at, or near, sources from which a potable supply of water can be obtained. Although the benefits of a protected water supply are great, it may happen, particularly in arid countries, where water is scarce, and towns and villages are inefficiently drained, that the introduction of a copious water supply to a town which had previously a scanty supply has an unfavourable effect on the public health. Moreover, if the soil is porous, the introduction of a copious supply to a town unaccompanied by efficient drainage will raise the sub-soil water level to a marked degree and predispose the place to malaria. In India there have been a great many instances where a protected water supply, just sufficient for drinking and household purposes, has had a marked effect in improving the health of the community, whereas in other cases a copious supply without efficient drainage, although it has eradicated cholera and other water-borne diseases, has been followed by malaria and a general decline in public health. Where a well or several wells are proposed to be used as a source of water supply, the tributary area of the well, particularly if sunk into recent alluvium, requires careful investigation. If a supply of water is required for irrigation, occasional failure is not disastrous, and in the "insecure" tracts of Deccan India, where irrigation wells and tanks fail one year in every eight or ten years, the crops obtained during the other years more than compensate for the loss of one year's crop. Scarcity or famine is only experienced after a failure due to two or three successive dry years. In the case of a public water supply, failure of supply cannot be regarded with the same equanimity, so that the minimum supply of the source, and not its average supply, should be considered as the supply available. In areas of more or less constant moisture, where the source of supply is from wells, it

is possible that the natural ground storage may render the yield ordinarily quite uniform, so that the draught from the wells can more or less exceed the minimum yield, and the effect of dry years be disregarded; yet in areas of uncertain rainfall, particularly where the depth of the water-bearing soil is not great, and where the proposed draught from the well or the demand nearly equals its estimated minimum yield, it will be advisable to neglect this element of ground storage.

The tendency is to waste, and in arid climates, where potable water is valuable, the people must be accustomed, at the initiation of a public water supply, to economy. A constant draught in excess of the yield from a well may in a year of extreme dryness result in a failure of supply, and if the ground water store is depleted it may take months or even years for the water to accommodate itself to the new conditions. Even in this humid country, numerous wells along the coast have been abandoned owing to the constant draught in excess of the yield draining the soil of the storage of past years, so much so that the salt water from the adjacent sea has entered the depleted soil and rendered the wells brakish, a condition from which, as far as our present experience goes, a well never recovers.

54. In the case of ground water flowing to some distant outlet, if y is the height of the level of the ground water plane of saturation above a horizontal impervious stratum, and x be the distance from any origin o, and assuming that the slope of the ground water plane of saturation is uniform, and that the flow is in stream lines parallel to the ground water plane, and the flow is capillary, the mean velocity of flow in a solid column of depth y is—

$$v = \frac{dy}{dx}\mathrm{M},$$

where M is the modulus of the water-bearing soil (para. 23). The discharge per 1 foot width of the section of ground water soil at right angles to the direction of flow will be—

$$q = y\mathrm{M}\frac{dy}{dx},$$

or

$$qx = \tfrac{1}{2}\mathrm{M}y^2 + c$$

for any other distance x_1

$$qx_1 = \tfrac{1}{2}\mathrm{M}{y_1}^2 + c.$$

$$q = \frac{\mathrm{M}}{2}\frac{y^2 - {y_1}^2}{x - x_1} = \frac{y - y_1}{x - x_1} \times \frac{y + y_1}{2}\mathrm{M},$$

which is equal to the tangent of the slope of the ground water plane to the horizontal at the locality × mean ordinate × the modulus of the water-bearing soil (*vide* Fig. 21).

Or if s is the tangent of the slope of the ground water plane to the horizontal between any two ordinates, and y the mean ordinate, $q = M \, . \, y \, . \, s$ and $v = Ms$.

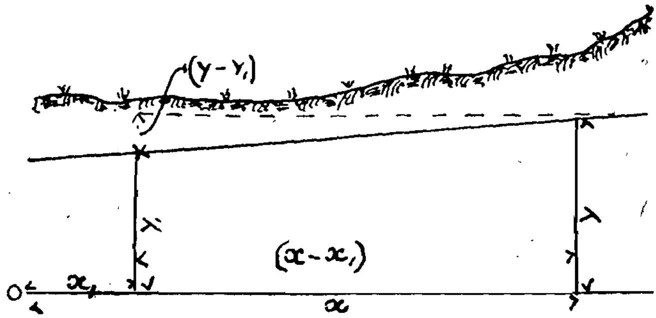

FIG. 21.

The above reasoning would be strictly accurate if the water-bearing stratum was overlaid and underlaid by impervious strata, and $(y - y_1)$, or h, was the difference in pressure as disclosed by boreholes sunk into the water-bearing stratum. If a

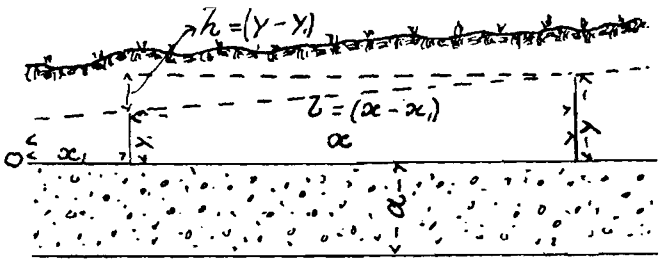

FIG. 22.

be the thickness of the stratum and l the horizontal distance between the boreholes (*vide* Fig. 22),

$$q = \frac{h}{l} Ma.$$

$\frac{h}{l}$ is the pressure gradient.

Fig. 23 represents a well of diameter $2r$ sunk H feet into water-bearing soil, the well being assumed to be sunk to an impermeable stratum. Accepting the conditions that no flow enters into the well from the bottom of the well, and that the flow into the well is radial, and flowing into the well through a series of concentric cylinders $yr \ldots, y \ldots, y_R$, measured above the assumed impermeable stratum at distances $r \ldots,$ $x \ldots,$ R, from the axis of the well. As the discharge into the well for any infiltration head h is constant, the velocity through any cylinder y multiplied by its distance x from the axis of the well is constant (*vide* Fig. 23), or

$$v_x \times x = c_1.$$

Also,
$$v_x = \mathrm{M}\frac{dy}{dx}.$$

$$\therefore c_1 \frac{dx}{x} = \mathrm{M}dy \text{ and } c_1 \log_e x = \mathrm{M}y + c_2.$$

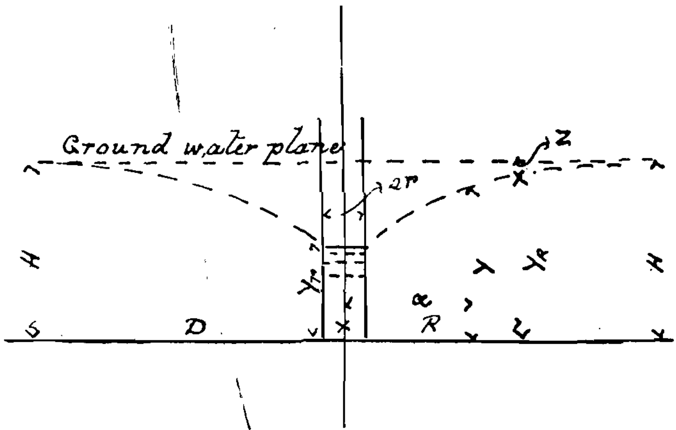

FIG. 23.

Also, $c_1 \log_e r = \mathrm{M}y_r + c_2$ and $c_1 \log_e \mathrm{R} = \mathrm{M}y_\mathrm{R} + c_2$.

$$\therefore c_1 = \frac{\mathrm{M}(y_\mathrm{R} - y_r)}{\log_e \mathrm{R} - \log_e r}.$$

If v_r is the velocity at the wall of the well, or velocity of entry,

$$v_r \times r = c_1, \therefore v_r = \frac{\mathrm{M}(y_\mathrm{R} - y_r)}{r \log_e \frac{\mathrm{R}}{r}};$$

the area of infiltration $= 2\pi r y_r$,

and the discharge into the well $\mathrm{Q} = \dfrac{2\pi \mathrm{M} y_r (y_\mathrm{R} - y_r)}{\log_e \frac{\mathrm{R}}{r}}$.

If h is the infiltration head when equilibrium is established, z is the drop in subsoil water level at radial distance R from the axis of the well, and H is the depth of the water-bearing soil to the assumed impervious layer, or the depth of water in the well before pumping operations were started,

$$Q = \frac{2\pi M(H - h)(h - z)}{\log_e \frac{R}{r}}.$$

z is the depth of the cone of depletion below the original ground water plane of saturation at radial distance R from the axis of the well, due to the infiltration head h at the well.

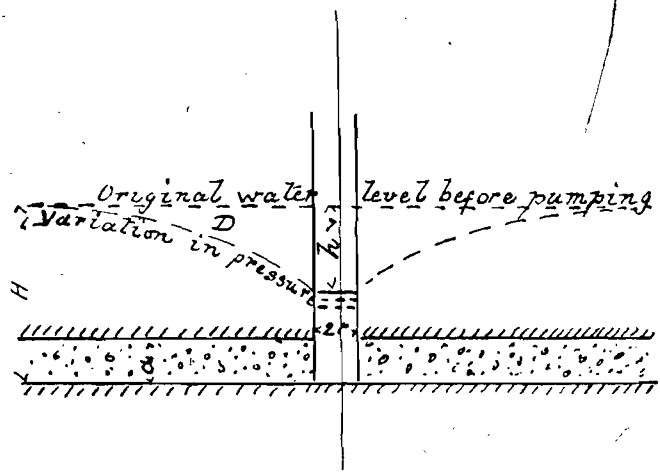

FIG. 24.

If D is the distance from the axis of the well where the draught from the well shows no appreciable effect on the ground water plane,

$$Q = \frac{2\pi Mh(H - h)}{\log_e \frac{D}{r}},$$

and this is a maximum when $h = \frac{H}{2}$.

If the water-bearing stratum is overlaid and underlaid by impervious strata the flow towards the well is radial. If a be the depth of the water-bearing stratum, and h the infiltration head when equilibrium is established, and $2r$ the diameter of the well (*vide* Fig. 24), the discharge or yield from the well will be

$$Q = \frac{2\pi M a h}{\log_e \frac{D}{r}},$$

where D is that radial distance from the axis of the well where the variations of pressure in the water-bearing stratum is uninfluenced by the draught from the well. In both the cases mentioned above the water is assumed to pass or percolate through the steining or wall of the wells as easily as through the subsoil.

55. If the lines of flow of ground water are represented by equidistant parallel lines, and the lines of flow into the well by radial lines forming equal angles with each other, the diagram (Fig. 25) due to Professor Schilter illustrates the flow of ground water towards a well, and the effect of the well on the lines of flow. The arc AB is the boundary down stream of the well from which no flow of ground water enters the well.

The velocity of flow towards the well from any distance x from the axis of the well, due to the draught or infiltration head h, is

$$v_x = \frac{Mh}{x \log_e \frac{D}{r}}.$$

If S is the normal slope of the ground water plane, the velocity of flow of the ground water when flowing in equidistant parallel lines will be MS, and when diverted to flow along any radial line will be MS cos θ.

Therefore the total velocity of water towards the well in any direction will be $MS \cos\theta + \dfrac{Mh}{x \log_e \frac{D}{r}} = v.$

At B (Fig. 25) $\cos\theta = -1$ and $v = 0$.

$$x \text{ or } OB = \frac{h}{S \log_e \frac{D}{r}}.$$

If $\theta = 90$, $\cos\theta = 0$, and OA = D.

Therefore, where there is a flow of ground water towards a well, the tributary area of the well is a strip 2D in width extending

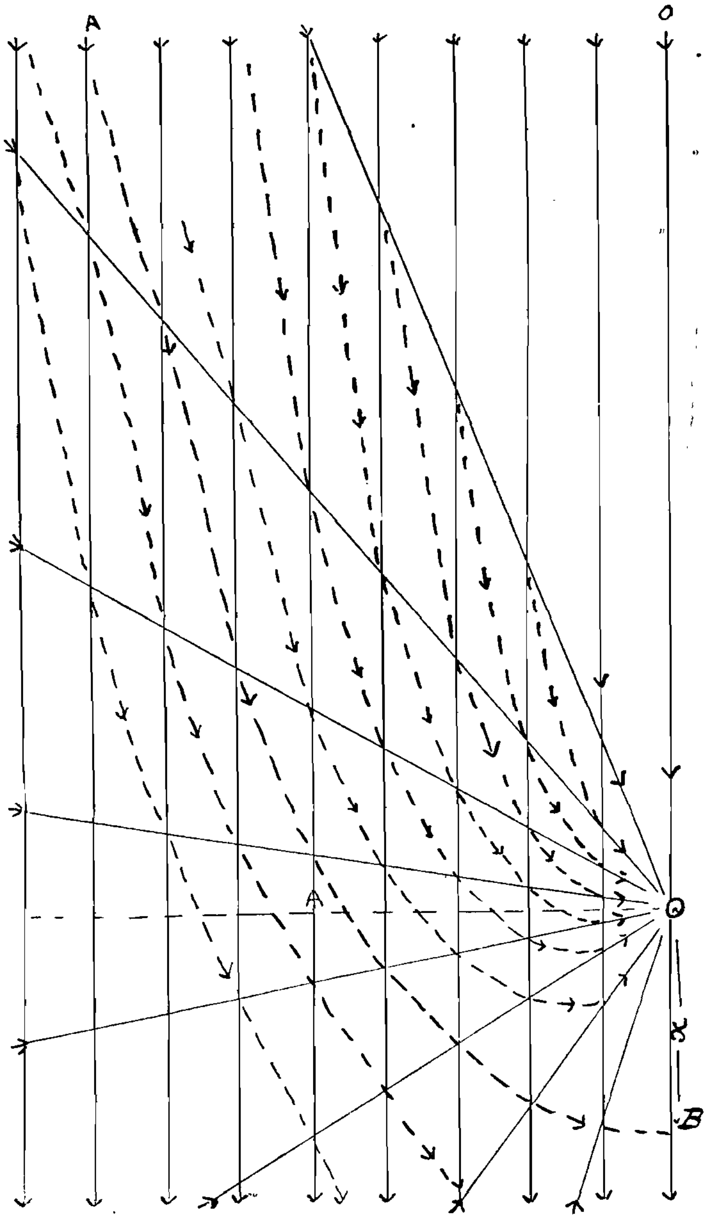

FIG. 25.

as far as the ground water contours show a fall of the ground water plane towards the well. If H is the depth of the water-bearing stratum, or the depth to which the well has been sunk into the water-bearing stratum, the volume of ground water flowing towards the well will be 2DH × the velocity of flow of the ground water, or

$$Q = 2DH \times MS.$$

This quantity is the maximum permanent yield of the well. If the draught from the well is in excess of this amount the well will in time fail. That is for a definite quantity of water to be drawn from a well for an indefinite period of time there must be an actual flow of ground water towards the well.

The ground water in the tributary area is replenished by—

(1) Rainfall on the exposed area which has penetrated to the ground water.
(2) Flood water of rivers over or alongside of the tributary area which periodically replenishes the ground water.
(3) Percolation or seepage from reservoirs, lakes, or bodies of water which replenish the ground water.
(4) Percolation due to irrigation from water drawn from a distant source.

For an extensive scheme for a water supply from wells, the actual estimation of the yield that may be expected from the tributary area is difficult. Rain is the chief source of ground water, but the catchment is often ill-defined. The only safe method is to actually ascertain the ground water contours over as large an area as possible, and the hydrographical survey of this area is carried out by careful observations of the water levels of all wells in this area. The observations should be made, if possible, before the wells are drawn on; a note should also be made of those wells at which there has been heavy pumping, or any considerable draught made on them. If old records are available, the original water level in the well before being put to use will be most valuable. The fluctuations of water level during the seasons of the year should, if possible, be recorded. Where time is available, the lag or time of replenishment of the wells after continuous and heavy rain should be noted. Observations at Ootacamund, South India, showed that the range of ground water level, for percolation wells, from the end of the monsoon period to the end of the dry weather period was 8 feet, and the supply to the wells lagged two months after heavy rain. The geological sections of the wells should, if possible, be ascertained and recorded.

The information obtained from existing wells should be augmented by sinking a series of bore-holes at such places that, with the observed water levels in the existing wells, ground water contours of the area under investigation can be drawn. The steepest slope observed from the ground water contours will be that of the general direction of the ground water flow.

The ground water contours should show, if possible, the levels of the ground water plane at the season of the year when the ground water level is at its lowest.

The velocity of flow of the ground water can be ascertained from the slope of the ground water plane and from the size of grain of the water-bearing strata (*vide* Chap. V.). The velocity may also be found by sinking a series of pipes at right angles to the direction of flow, and one or more pipes a fixed distance of about 100 feet above this line. A coloured liquid or a solution of permanganate of potash is poured into the upper pipes, and water is drawn from the lower pipes until the water changes colour; the time taken in transit gives the actual velocity through the pore spaces of the soil. Or a solution of salts is poured into the upper pipe or pipes and water drawn from the lower until the salt is detected. To obtain the value of M the porosity of the water-bearing soil should be ascertained or estimated. Generally, for sand, about 35 per cent. to 40 per cent., so that if $v =$ the actual observed velocity, $M = 0{\cdot}35v$ to $0{\cdot}4v$.

M is best obtained by sinking into the water-bearing stratum a tube well, through the strainer or steining of which water passes as easily as through the water-bearing soil; and from measurements of the discharge under various heads to estimate M from the formula given in paragraph 54. Then, if L be the length to be occupied by a line of wells at right angles to the direction of flow;

H the depth of the water-bearing stratum, or depth the wells are sunk into it;

S the slope of the ground water plane;

The volume of ground water supplying the wells will be—

$$Q = MHS(L + 2D).$$

D is generally assumed to be about 1000 feet.

If the area is not periodically fed by floods or surface waters, but the supply to the ground water is entirely dependent on rainfall alone, the supply or percolation to the ground water must be estimated on the principles laid down in Chapter IV. That is, the percolation will be the rainfall less losses due to

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Name of Town.	Mean Annual Rainfall.	Maximum Rainfall.	Minimum Rainfall.	Mean of the Lowest Three Consecutive Dry Years.
	Inches.	Inches.	Inches.	Inches.
Bellary	19·0	35·02	7·23	13·09
Adoni	26·28	53·31	11·25	19·37
Anantapur	20·29	37·12	3·90	14·52
Cuddapah	32·01	58·50	9·46	19·99
Kanigiri	24·49	38·84	6·45	16·98

The number of periods of consecutive three dry years in which the mean of the three years is below the mean annual rainfall is seven during forty-eight years' record.

It is obvious that a water supply to any of these towns from percolation wells, which depend solely on that portion of the rainfall which percolates to ground water for their replenishment, will be extremely precarious. In a year of minimum rainfall, and in periods of successive dry years, the replenishment to ground water must be small. So that unless the water-bearing soil is of great depth, and the area of exposed surface very large, other sources must be looked for.

The British Association have laid down the following questions to be answered in the case of reports on wells :—

(1) The exact position of the well.
(2) When was it sunk?
(3) What is the total depth of the well?
(4) What is the depth of water below ground surface (i) end of winter; (ii) end of summer.
(5) At what time of the year is the water level in the well highest, and at what time of the year is it at its lowest level? Is this level stationary, or are there signs that the level is rising or falling?

(6) What is the character of the water ?
(7) Give the strata as far as possible through which the well has been sunk.
(8) Does surface water percolate into the well ?
(9) How long does it take before wet weather causes the water in the well to rise ?
(10) Any further remarks.

The time available, and the funds allotted for the investigation, generally limit the amount of detail information that can be collected.

In the absence of detail data as indicated above, the simplest procedure is to sink a test well at the site where it is proposed to sink the permanent wells; which site is selected from the information obtained of the strata of existing wells, supplemented by that of bore-holes. The well should be sunk to the full depth it is proposed to sink the permanent wells. The well should be then pumped dry or to its critical head (*vide* par. 65), and the

Distance Apart of the Wells in Feet.	Mutual Interference. Per Cent.	Distance Apart of the Wells in Feet.	Mutual Interference. Per Cent.
100	65·8	600	14·0
200	45·0	1000	6·4
400	24·0	—	—

time taken for the well to recoup to its original level, or nearly its original level, noted. The safe yield will be the total quantity pumped out for the sum of the time occupied in pumping out the well and the time taken for the well to recuperate.

Thus, if 30,000 gallons are pumped out of the well in three hours and the well takes nine hours to recoup, the safe yield from such a well will be 30,000 gallons in twelve hours. In observations for recoupment the last few inches take a considerable length of time to fill up, and an allowance of 3 inches or 6 inches may be made, according to the nature of the water-bearing stratum. It is obvious that the yield test should be made when the ground water plane is at its lowest level.

In England the lowest level of ground water is usually in autumn, and wells are at their highest in February. The number of wells for a permanent installation will depend on the extent of the water-bearing strata as disclosed by borings, and the installation will consist of a line of wells at right angles to the general direction of ground water flow. No draught in excess of the safe yield should be taken from each well, assuming that the wells are their full distance (varying from 600 to 1000 feet) apart. The statement (p. 104) shows the mutual interference of a number of wells in a row. The wells are assumed to be 6 inches in diameter, through the steining of which water passes as easily as through the soil, and the infiltration head is 10 feet.

56. All rocks, whether igneous or sedimentary, however massive or solid, are traversed by fissures or joints, which are liable to be opened out by the mechanical and chemical action of ground water, or by movements of the earth's crust. Although certain rocks are permeable, and when tapped by wells yield water, the movement of ground water across long distances must take place in a great measure through fissures and passageways larger than the pore spaces of the rocks themselves, and the mathematical treatment of flow becomes inapplicable except when dealing with small areas of permeable rocks. Often the rocks, more especially the igneous rocks, are decomposed or disintegrated to a considerable depth, and sometimes water percolating down some fissure or joint may cause disintegration at considerable depths below the surface, and a disintegrated layer of rock may be found below solid rock. Generally, the decomposition is least near the solid and unaltered rock, and the disintegration gets greater as the surface soil is approached. Above the alluvial valleys in what may be termed the rock area of a country, on steep slopes, and along beds of streams, the surface soil, and sometimes the disintegrated sub-soil, is washed away; while on the plains there may generally be found a deep surface soil underlaid by a thick stratum of disintegrated rock. In such formations, where there are no permanent streams near which a well would generally be sunk, the lowest part of the centre of a valley, if broad and open with easy slopes, or the junction of two or more such valleys, is the most suitable place for sinking a percolation well.

When it is desired to obtain water from a formation known to be entirely superficial, or from recent alluvial deposits, the most favourable position for the search will be in the lower parts of the plain succeeding the intersection of the primary and secondary valleys.

No springs of importance will usually be found at the heads of valleys, but they are generally met with at the intersection of secondary valleys with the principal ones of the formation. As also occurs with surface waters, the volume yielded by any underground springs is proportional to the length of the valley, or tributary area of the springs, and the latter is always greatest when the secondary valleys of a hydrographical basin form an acute angle with the direction of the main valley. Where the valleys are steep, not only will the rain-water have less chance of entering the sub-soil before it flows off the ground into streams, but owing to the denudation of the soil by the rapidly flowing water, there will be less depth of soil, and sub-soil to hold the water which does percolate in. Consequently broad open valleys with easy gradients furnish better sites for wells than narrow valleys with a rapid fall.

Superficial formations are not generally of great depth, and as the hydrostatic pressure on the ground water is small, if large supplies are required it will be necessary to form a species of reservoir to store the water flowing during the intervals of its withdrawal from the soil. For small depths it is more economical to sink a percolation well than to put down a bore-hole, and as the size of a percolation well usually enables it to perform the function of a reservoir, we find that water is almost always obtained from superficial deposits by percolation wells.

In what may be termed the "rock well" area, as distinguished from the alluvial areas, the underlying rock has not the same capacity for holding and storing water as the alluvial deposits, such as sand and gravel have. It is therefore of the utmost importance that the water, particularly in dry continental climates, should be conserved in the sub-soil as far as possible by constructing tanks or small reservoirs across valleys or lines of surface drainage above the wells, so as to impound the surface flow which would be otherwise lost, and increase the percolation into the well. In the Cuddapah district of the Madras Presidency, South India, the restoration of an ancient tank, so as to hold up some 20 feet of water, improved the supply to all the irrigation wells in the area below the reservoir embankment to the extent of about 500 acres, the sub-soil being the tilted shales and limestones of the Cuddapah series of the Vindhyan formation. In another case a reservoir, constructed by throwing an earthen dam across a valley filled with talus and debris from the hills forming the sides of the valley, impounded only 4 inches of an annual rainfall of 40 inches, in a humid climate near the coast; the remainder, except for one or two exceptional falls of rain, which passed off in floods, percolated to the ground water. In a year of exceptional dryness, when the reservoir failed, a fairly sufficient supply for the needs of the town was obtained from an infiltration gallery below the reservoir embankment.

The tanks required to hold up the surface drainage and assist percolation into the soil, are generally small affairs, consisting of earthen banks holding up some 5 or 6 feet of water, and passing extraordinary freshets round their flanks by paved by-washes. Even if these tanks are beyond the funds of a cultivator, and the well is of some depth and diameter, the natural surface drainage can be diverted into the well, and thus passed back into the sub-soil. It has been ascertained by direct experiment that any description of well can absorb as much water as it is able to produce. In this way a large amount of water may be stored in the sub-soil during the wet or rainy season. The well may require periodical clearing of silt, unless the surface water is first passed through a settling-pond.

In tracts where igneous rocks obtain, ground water is chiefly stored in the decomposed and disintegrated areas. Wells, therefore, in this area should be sunk or blasted out when there appears to be a considerable amount of distintegrated rock and surface soil at as high a level as possible above the bottom of the well.

56A. A question that often arises in these "rock well" areas, more especially in the case of irrigation wells in India, is whether an increased supply of water can be obtained by deepening a well, or increasing its diameter, or driving adits or headings from the well. Increasing the diameter of a well may give a slightly larger cone of depletion, but the possibility of tapping additional fissures is remote. Lateral adits give better results, but at least three or four adits must be driven in different directions to make the possibility of tapping fissured rock more certain, and in countries where funds, pumping appliances, etc., are not available, these adits are expensive and not easy to make. The simplest and most economical method is to deepen the well.

The local well-sinkers in India excavate the hard rock as far as their primitive appliances and explosives enable them to do so, and then widen the well as far as their finances permit, to obtain storage. As there are numerous joints and fissures in the hardest rocks, it is possible that a water-bearing fissure may be tapped in deepening the well, thereby connecting it with a remote underground reservoir of decomposed or disintegrated rock.

Where a well has already been sunk, and an increased supply is found necessary, the simplest procedure, in order to ascertain the possibility of there being water-bearing fissures at a greater depth than the well, is to sink a 4-inch or a 6-inch bore-hole inside the well to a depth of 50 feet or 100 feet, or to a greater depth if required, and "torpedo" the well, that is, exploding a charge of 100 quarts, or even 200 quarts, of nitroglycerin at the bottom of the bore-hole. The nitroglycerin is lowered into the well in a series of canisters $3\frac{1}{2}$ inches or 5 inches in diameter and 10 feet in length. The charge is exploded by a "Go Devil Squib," holding about a quart of nitroglycerin and furnished with a percussion or time fuse.

57. Treating the case of wells generally, the supply obtained from percolation wells, unless such wells are sunk in large areas and great depths of water-bearing deposits of sand or gravel, is rarely of a sufficient copious nature to supply the requirements of large towns, and there is always the possibility of the drainage or sullage of such towns percolating into the water-bearing area, if it should be adjacent to the town, and polluting the supply. In these circumstances it may frequently be found advisable to obtain a supply from the water-bearing strata underlying the superficial deposits, or even, when more than one water-bearing stratum exists, to resort to a lower one. The water in these underground strata being generally under pressure, a much smaller size of well will then suffice to ensure a constant supply, because the lower water-bearing stratum constitutes a natural reservoir. It is in such cases that it is found advisable to resort to boring.

The depth of the masonry well will then be such that a sufficient depth of water is obtained in it for the working of the pump or other appliance used for raising the water, and its diameter such that the water-lift used can easily work in it. That is, the masonry portion of the well will be sunk to a depth below that to which it is known the water will rise when the water-bearing stratum is tapped, so that there is sufficient water for the water-lifting apparatus to work in; and the well will require to be of such an area that the water-lifting apparatus can easily work in it, and beyond that depth the well will be continued as a bore-hole to the water-bearing stratum. This method combines the cheapness of the artesian well with the space necessary for the introduction into the well of the water-lift in general use. As already pointed out (par. 56), where existing percolation wells give a short or inadequate supply, this yield can be increased by sinking bore-holes in them to water-bearing strata situated at lower levels, if the geological conditions of the locality indicate that such strata can be tapped at comparatively reasonable and economic depths. But it must be borne in mind that invaluable as are the indications of theoretical geology in this as in all branches of engineering, the inductions derived require to be verified by actual experiment.

To return to the consideration of percolation wells only, the subjects to be considered are the diameter and depth to be given to the well, and the manner in which the sides are to be consolidated. It is evident that the diameter and depth of a well are not susceptible of any absolute mode of determination. Local circumstances will cause them to vary in every case, not only because the water-bearing stratum itself is of a different nature, but also because the rate of consumption from the well differs in each of them. A careful examination of wells already executed, or a comprehensive geological and hydrographical survey of the locality is necessary before commencing such works. Should any wells exist, the dimensions to be given to a new one to be formed will be ascertained by observing the height of the level of the ground water plane of saturation in the existing wells at different seasons of the year, and the rate of supply must be ascertained by observing the extent to and manner in which the water may be lowered by pumping. In some cases it may be necessary to ascertain the extent of the tributary area and the rainfall on it, or other sources of supply to the ground water, in order to form a correct opinion as to the capabilities of the source of supply to meet any other demands that may arise. Before founding any establishment depending upon its supply of water from ground water, it becomes essentially necessary to ascertain all the circumstances affecting the possibility of the supply being cut off or diminished by the construction of other wells in the vicinity.

When the extent to which it is possible to lower the rest level of the water has been decided, the depth of the well will be such that the suction of the pump shall always be below the water surface. If the supply coming into the well is amply sufficient to meet the demands of the pump, a depth of from 4 to 6 feet below the permanent level of depression, or infiltration head, will in most cases be found sufficient. If the demands of of the pump are greater than the yield of the well, and periods of rest are necessary to allow the well to recoup, the depth of the well should extend to the full suction power of the pump. In the case of wells sunk in sand, attention is invited to Chapter X.

58. The manner in which the sides of a well are to be lined or steined will depend on the nature of the strata traversed, the object being to prevent the sides from falling into the well; and if the well or wells are for a public water supply, the steining must be of an impermeable character in order to exclude sub-soil water and surface drainage, as may be likely to contaminate the water of the lower stratum.

In the case of wells which are sunk by excavating the material within the steining, further lengths of steining being added as the well sinks, the steining, of whatever material it be constructed, is put together or built upon a bottom curb made with a cutting

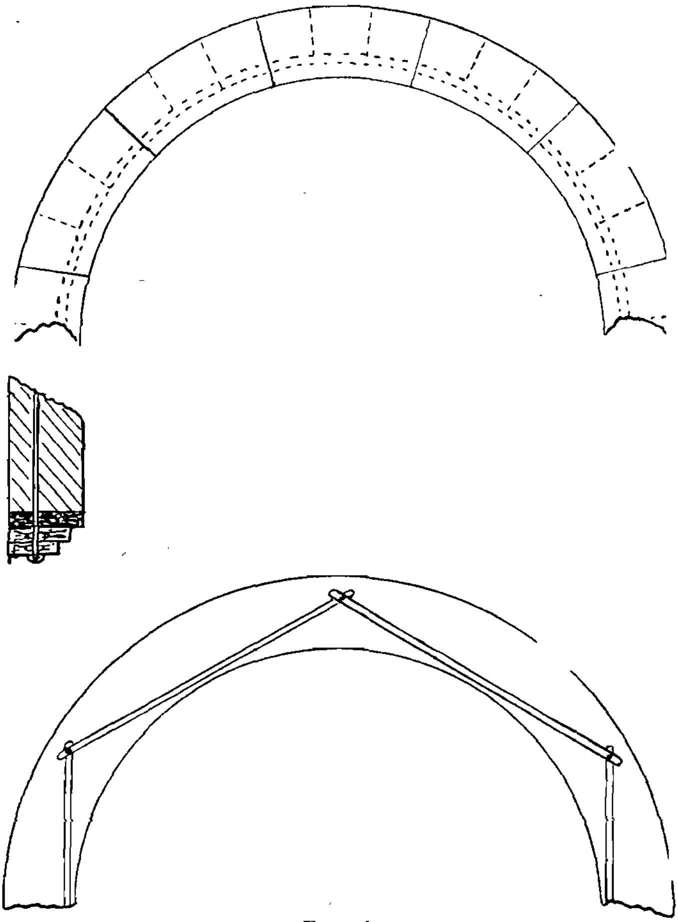

FIG. 26.

edge. For ordinary purposes, the curb is made of hard wood, and of a thickness varying from 6 to 18 inches. The curb is made of the size of the well, and consists of pieces of wood nailed together in a circular form, the upper layers overlapping the lower ones, the outside edge of the lowest layer being generally finished off with an angle iron (*vide* Fig. 26). The object of the curb is to take the strain caused by the ground underneath one side of the well offering a greater resistance to the sinking of the cylinder than the ground on the other side. It must therefore be made strong enough to withstand considerable strain.

A simple form of iron curb may be made of a flat horizontal ring of $\frac{3}{8}$-inch boiler plate about 2 feet 6 inches wide, riveted by an angle iron to an outer cylindrical ring of similar plate 18 inches deep, and having gusset plates underneath the horizontal ring connecting it with the vertical cylindrical ring. The outer cylindrical ring extends 3 inches above the horizontal one, forming a support all round to the base of the brick cylinder, on the outside; and an angle iron on the inner edge of the flat ring forms a similar support to the inside edge of the masonry steining.

The curb is first fixed in position and sunk until the top of the curb is flush with the soil or sand. On it about 4 to 6 feet of masonry is built, and when the mortar has set and hardened, the material inside is scooped out so that the curb and masonry descend; another 4 or 6 feet of masonry is added, and again the same process resorted to, and the curb with the steining made to descend until any required depth is attained. Great care has to be taken that the stuff is scooped out gradually and evenly all round, so that the masonry may not crack in descent. It sometimes happens that the resistance to sinking is so great, particularly if debris gets in between the steining and the soil, that the cylinder will not sink even when all earth or sand under the well has been removed. When this happens it is clear that the well curb, and the lower part of the well cylinder, are suspended with no support except the tenacity of the mortar, and danger lies in the well curb being detached from the lower part of the cylinder, or the lower part of the cylinder may crack off from the upper. To guard against this danger six or more rods of iron $\frac{3}{4}$ inch, or of a greater diameter, are passed through the curb vertically up through the masonry (*vide* Fig. 26). These tie-rods vary in length; for ordinary wells they are from 6 to 8 feet in length, their upper screwed ends passing through iron strap washers, are fitted with nuts, which are screwed down. By this means the lower part of the well is firmly braced to the curb.

It is a good practice to keep the well cylinder heavily weighted during sinking, as it assists to overcome the frictional resistance between the cylinder and the soil in which it is sunk, driving the cylinder into the soil, and thereby lightening the labour of sinking. It also counteracts the tendency of the well curb and the lower part of the cylinder to separate from the upper part. When the top of the cylinder has sunk as far as it can be sunk, the weights are taken off and another section built up. This section should be allowed to set and harden, generally about a fortnight, during which time the mortar must be kept damp so as to cause it to set and not dry. When the mortar has set and hardened, the weights should be replaced and the sinking resumed. Weights are generally placed on the cylinder in the following manner. Timber baulks are laid across the cylinder, and the parts projecting outside the well opening are planked over, so as to form a platform surrounding the well opening, on which sandbags or iron bars are placed in order to obtain the requisite weight. Should the well cylinder in sinking get out of the perpendicular, the weights on the side it has sunk too much should be removed and placed on the side it has sunk too little.

59. The frictional resistance to the sinking of a well increases with the depth, so long as the amount of stuff dredged, or removed from the well, equals the amount of soil the well displaces; but it frequently happens that considerably more stuff is removed than the contents of the well, and the stuff, especially in the case of sand, runs or flows in under the curb causing the well, and the adjoining soil surrounding it, to sink together. If this flow of soil from any cause does not run equally all round into the well, the well may jam, or stick, in its course downwards, and commence to go out of position. It is therefore important, in the case of wells of large diameter, to be sunk to depths of 50 feet and deeper, that the weight of the steining should be such as to cause the well to sink by its own weight, before the amount of material dredged exceeds the column of soil displaced by the well. A well should keep continually sinking, so as to cut off the outside material entering it, and thus reduce the amount of stuff to be excavated. A light well would only drop at intervals, and far more stuff would be dredged out than the volume content of the well sunk; a heavy well, on the other hand, would keep continually sinking, and thereby cut off the outside material flowing in.

Sir Robert Gales, M.Inst.C.E., has introduced a term called "sinking effort" per square foot of the outside skin of the steining. That is, the total effective weight of the well steining plus any extra loading on the well divided by the area of the skin or outside surface of the steining below ground level. As deep wells for a water supply are generally sunk through saturated soil, the effective weight of the steining is its weight in water.

For all practical purposes, in the case of wells sunk through "recent" alluvium, the sinking effort in *cwts.* per square foot of the skin of the steining is one-thirtieth of the depth below ground surface the well has to be sunk. That is, if borings disclose that in order to obtain a copious supply of water it will be necessary to sink a well to a depth of 120 feet, the sinking effort per square foot will be 4 cwts., from which figure the necessary amount of thickness to be given to the well steining can be deduced. It is obvious that if the steining is of sufficient weight for the well to be sinking as excavation proceeds, the expense and the delay in placing and removing the surcharged weights, when a new course of masonry has to be added, are obviated.

60. *Well Sinking.*—Generally, but not necessarily, an excavation somewhat larger than the outside diameter of the well is first made, and carried down to within a foot or so of the subsoil water level, and the well curb bedded at that level. Where such excavations are made, considerable care is necessary to keep the annular space between the sides of the excavation and the well steining clear of debris falling from the sides, as they are apt to get between the cylinder and the soil, thereby causing a considerable resistance to the sinking of the well. When the curb has been bedded the first section of the steining is built up. Men then enter the cylinder and excavate the material from under the well curb, the stuff being raised by baskets or skips, and the cylinder is sunk in this manner until there is too much water in the well to allow the well-sinkers to work. The stuff is then excavated and raised by a Bulls or similar hand dredger worked from a derrick fixed over the well. In North India the well-sinkers use a local excavator called a "Jham," which resembles a large hoe, with a handle at an angle of about 30° to the blade. The advantage of this hand dredger is, that it can be worked faster than a Bulls dredger, and it can also be fixed right against the well curb, owing to which, when the strain on the rope brings the blade into a horizontal position, the movement of the blade sucks the stuff from under the well curb into the well.

In the improved form of "Jham" the scoop is made of sheet iron 2 feet 2 inches wide and 2 feet 4 inches long. The front edge of the scoop is made thin and sharp, and the scoop is supported by a stay connecting it to the handle; its weight is about 1 to $\frac{3}{4}$ cwt.

The method of using the "Jham" is as follows. By means of a thin rope attached to the socket end of the arm E (*vide* Fig. 27) the Jham is lowered by hand to the bottom of the well until the cutting edge *c* and the outer end of the arm A rest on the soil. Then, with the weight of two or three men bearing on the top of a pole F (which is held in place by a pin or point at its lower end passing easily through a socket at the tail end of the arm E), the scoop is raised up a short distance by the thin rope, and then dropped, its cutting edge being thus forced into the soil. By repeating these strokes the scoop is forced into the soil until it is buried sufficiently deep enough into the soil. Then, with the weight of the men still on the pole, the Jham is hauled on by the main rope fixed to the end of the arm A, by means of a windlass, or block and tackle from a derrick fixed over the well, thereby tilting the Jham unto a horizontal position. The pole is then removed, and the Jham is brought up filled with material. There are other forms of excavators, but the Jham is the simplest, and easily worked, and there is nothing that can be destroyed.

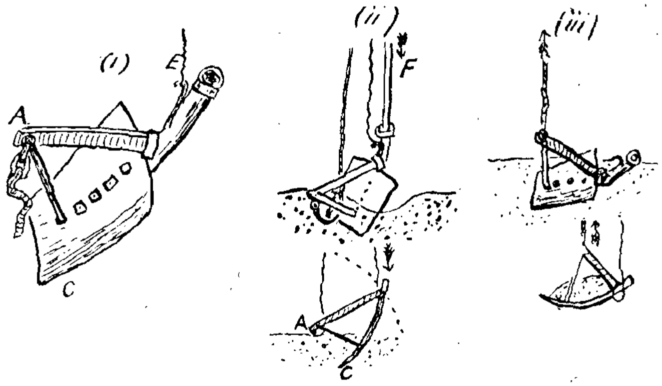

FIG. 27.

When a well will sink no longer, owing to some obstruction or swelling of the ground, if the water-bearing stratum has not been tapped and the well can be unwatered without danger of blowing, the well should be pumped dry and a smaller diameter well sunk within the larger well.

In the case of large and deep wells special curbs are necessary, which are built up of iron plates, or made in ferro-concrete, and the material is excavated and removed by dredgers, of which there are various types, worked by steam or other power hoists.

Where the sub-soil is of such a character that a well cannot be sunk as above described, and the quantity of inflowing water can be overcome by the pump or baling apparatus used, the excavation is first carried out and the steining built up from the bottom of the well, the well being kept unwatered while the work is in progress. In such cases a well curb is obviously not necessary. If the soil is such that it cannot stand vertically for any great depth, in order to guard against danger to workmen, and to prevent the sides falling in, the well should be carried out in a series of ringed steps, the upper rings being steined before the lower ones are excavated (*vide* Fig. 28). The thickness of the steining in this case being only sufficient to prevent the sides from falling into the well, and in many cases, if the well is not to be used as a source of potable water supply, the steining may be executed without mortar.

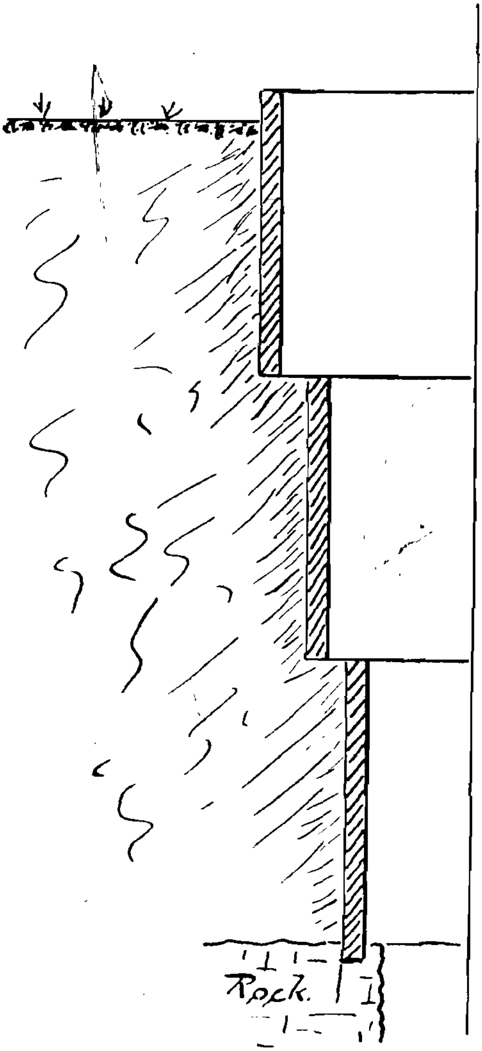

FIG. 28.

61. In the construction of artesian wells the preliminary investigations require to be of a more elaborate nature than those necessary before constructing an ordinary percolation well. It is necessary to ascertain the relative heights of the outcrop of the water-bearing stratum, and its nearest overflow with respect to the position of the proposed well, in order to arrive at some conclusion as to the probable height of ascension of the water when it shall have been reached. It is also necessary to ascertain the surface of the outcrop, and the thickness, of the water-bearing stratum in its passage beneath the impervious

upper stratum, for upon these conditions will depend the capacity of the former to yield a constant supply.

The existence of any fault or dislocation of the strata must also be carefully sought for, because should such exist, either the water contained in the permeable stratum may find a more ready outlet to a lower level, or its circulation may be cut off from the particular part of the basin where it is proposed to place the well. In the tertiary strata the conditions requisite to ensure the success of an artesian well are more likely to be met with than in the secondary formation. Generally speaking, the tertiary strata are composed towards their base of sandy permeable materials, covered by impermeable clays. They are also less frequently interrupted by disturbances of the strata, for there do not appear to have occurred any great geological upheavals subsequent to their deposition. Their circumscribed areas also render it more easy to calculate the influences of the different phenomena affecting the flow of water within them. In nearly all formations, however, the general law prevails by which the base is constituted of a series of sandy permeable deposits marking the epoch of change from one geological condition to that immediately succeeding it, and these permeable deposits are covered by others of a totally different character. It almost always happens also that the outcrop of the permeable strata occurs at an elevation superior to that of the position in which it is usually required to bore for water. In many cases, also, compact limestones acquire the facility of transmitting a subterranean current, either by their being traversed by great clefts or from their being fissured in every direction. If we cannot predict with certainty in what formation water will be found, this much is certain, that the primary and transition or metamorphic rocks are never likely to exist under conditions requisite to ensure the success of an artesian well. In sedementary rocks much affected by geological disturbances, or in elevated districts which are not surrounded by the outcrops of a permeable stratum at a higher level, and passing beneath those thus operated on, there can hardly be said to exist any reasonable prospect of success. It is only in regular stratified deposits which have not been subsequently disturbed that there can be said to exist any certainty of obtaining a supply by the construction of an artesian well.

62. Observations taken of the yield of an artesian well and the pressure of the issuing water, or in cases where the ground surface is above the static head or rest level, of the water in an artesian well, show that in both cases the supply is almost directly

proportional to the decrease in pressure, or depression below the rest level of the water, so that the discharge from such wells can be mathematically represented by the formula

$$Q = Kh,$$

where Q is the discharge from the well;

h is the decrease in pressure in a flowing well, or depression below the rest water level where the water is raised by pumping, and which may be called the head producing discharge.

K is a co-efficient depending on the size and nature of the pipe, and on the character of the water-bearing stratum tapped.

In the case of a flowing artesian well, where the water issues some height above the ground level at the well, if H be the static head of the issuing water, for any decrease in pressure h the energy available at the well will be

$$Kh(H - h).$$

This is a maximum when $h = \frac{H}{2}$.

The maximum energy obtainable from such a well will be

$$\frac{KH^2}{4}.$$

It will be thus seen that at all flowing artesian wells energy at the locality of the well is obtainable, the amount depending on the discharge and the static head.

63. In the case of a public or domestic water supply, if land springs and surface drainage are to be excluded, it becomes necessary that the materials employed for the well steining should be of such a nature as to resist permeation through their substance.

In civilised countries, where funds are generally available, a protected water supply is regarded as essential to a community, but the pioneer engineer, and the engineer providing water supplies to villages and hamlets in the East, has to rely on his own resources to protect the source, and the distribution of drinking water. In selecting the source, it is well in all cases to obtain local information as to the sources of drinking water generally used by the people. Their reasons for the use of a particular source is often beyond our knowledge of what constitutes a good or bad water. The people in the south of India will say that the water of the Cauvery river is beneficial to their bodies, as it contains gold; whilst the water of the Tambrapani river further south is not so beneficial, as it contains copper. It is true that the upper waters of the Cauvery drain the Mysore plateau, which is composed of granitoid gneiss with veins of quartz, and where gold is found; whilst the Tambrapani drains the Western Ghats, where laterite overlying syenite predominates, and what is most remarkable, the crops irrigated by the Tambrapani river produce the heaviest crops in the Madras Presidency, the outturn per acre being nearly 30 per cent. above the average for the whole Presidency. The river Ganges, in Northern India, is famous for two things—its alleged purifying influence over all who bathe in it, and the large quantity of silt carried down by it in suspension, which gives it its characteristic turbidity. For ages there has been a belief among the Hindus that bathing in the Ganges, particularly at Benares, is a safeguard against cholera, typhoid fever, and other infectious diseases. A recent analysis of the river water at Benares has revealed the fact that the Ganges is alive with bacteria antagonistic to the health of these pathogenic bacteria.

Some people will drink from ponds covered with a dense mass of green algæ and declare the water beneficial to the digestive organs. Others say that water for the household should be drawn before sunrise, and should be stored in clean copper vessels.

In India the people, as a rule, prefer river or running water to water from wells. Most of the large rivers of India are sacred, which may account for their popularity; but the reason is possibly that river and stream water are softer than well water, and are therefore more appreciated by a people, the greater part of whom are vegetarian in diet.

It is generally advisable to allow the inhabitants of a village to obtain their supply directly or indirectly from their accustomed source, unless the possibilities of pollution are so great that purification can only be obtained at a great cost. If a stream or river, not subject to great pollution from towns and villages on its banks, is the usual source of supply to a village or town, sinking wells in the water-bearing soil adjacent to the river or stream, with precautions to be mentioned later, will enable the inhabitants to obtain the water they are accustomed to, with the advantage of filtration through the soil before use. Where wells are replenished by the flood waters of rivers alongside, or flowing over the tributary area of the wells, which are put down for a domestic water supply, cases of periodic pollution, in times of drought (i.e. due to insufficient dilution of sewage effluents) or during floods, must be specially guarded against, and wells should not be placed in the alluvium of the river beds nearer than 100 yards from the river.

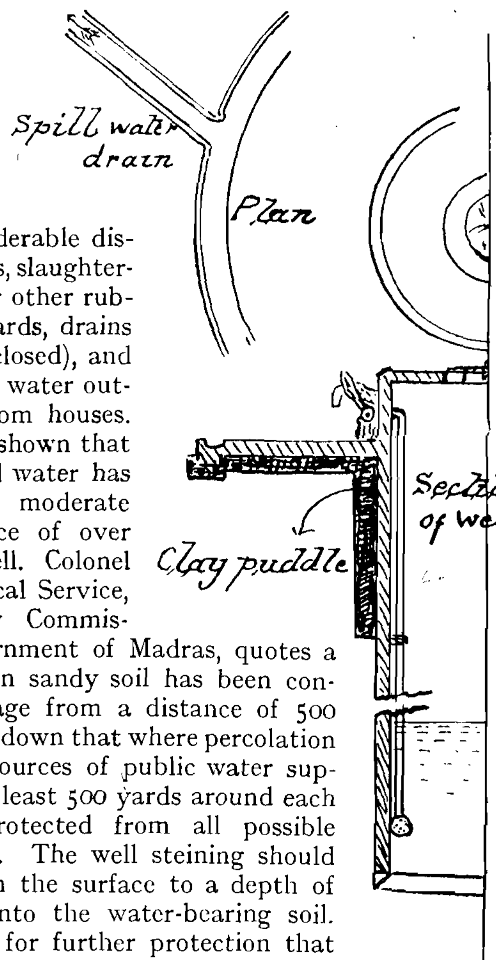

FIG. 29.

For a small community a well is the most suitable and economical source of potable water. Such a well or system of wells should be situated at a considerable distance from cesspools, slaughter-houses, middens, or other rubbish heaps, graveyards, drains (whether open or closed), and from natural storm water outlets, particularly from houses. Experiments have shown that the level of ground water has been lowered by moderate pumping a distance of over 1000 feet from a well. Colonel King, Indian Medical Service, sometime Sanitary Commissioner to the Government of Madras, quotes a case where a well in sandy soil has been contaminated by sewage from a distance of 500 yards; and has laid down that where percolation wells are used as sources of public water supplies, an area of at least 500 yards around each well should be protected from all possible sources of pollution. The well steining should be impervious from the surface to a depth of at least 25 feet into the water-bearing soil. It is also advisable for further protection that the outer circumference of the steining is puddled a thickness of 1½ feet to 2 feet, extending to a depth of 10 feet, from the ground surface; and a masonry platform some 10 feet diameter should be built around the well over a puddled foundation connected to the puddle collar round the steining. A small masonry drain should lead off the spill water from the platform to the nearest natural drainage course, to prevent stagnation near the well (*vide* Fig. 29).

The well should be covered and fitted with a pump. Here the difficulty arises; it is surprising how easily these pumps are broken by the rural population of the East, and this is followed by the cover of the well being broken open, and pots and buckets indiscriminately let down for water. An easily manipulated and foolproof pump is a great desideratum for rural water supplies in the East. Failing pumps, the well must be provided with buckets, so that the people do not let down their own pots and vessels for water. The ideal well from a sanitary point of view is where the steining passes through a stratum of clay or other impervious stratum of some depth before striking water-bearing sand. Shallow wells are most liable to pollution from houses, farms, and cultivated lands. Sub-soil wells obtain a supply from a greater depth, and pollution can be avoided by proper care. Deep-seated wells are sunk to reach water-bearing strata at a depth from the surface where the water is generally free from organic pollution, unless a fissure in the rock should bring surface polluted water to the well. The water of deep-seated wells is generally hard, owing to the dissolved gases and minerals it has derived from the rocks through which it has passed before reaching its present position.

In European countries, in the case of deep wells, the steining sometimes consists of cast-iron tubes 1 inch to $1\frac{1}{2}$ inches in thickness, and about 5 feet in diameter, and in lengths of 5 feet; they are cast with internal flanges, and are coated with Dr. Angus Smith's solution, or other rustproof composition. The tubes are bolted together, the joints being machine faced, and made with hemp and red lead, and the caulking face filled with a rust jointing material. Cement grout is run into the annular space between the cylinder and the soil. Fig. 30 gives an example of a well for a public water supply sunk in chalk.

Where the depth of chalk or water-bearing rock is not at any great depth from the ground surface, a pilot shaft is first excavated through the surface soil and timbered. The well is then excavated by jumping a heavy boring chisel consisting of a built-up riveted frame of mild steel, fitted with ten or more cutting chisels and points, which are removable, so that they can be renewed. The broken stuff or slurry is removed from time to time by a grab-dredger, which is operated by the boring winch. The lining is forced down as the excavation proceeds, or the whole lined depth is first excavated, and the tubes are jointed up on the surface one at a time, and floated by means of

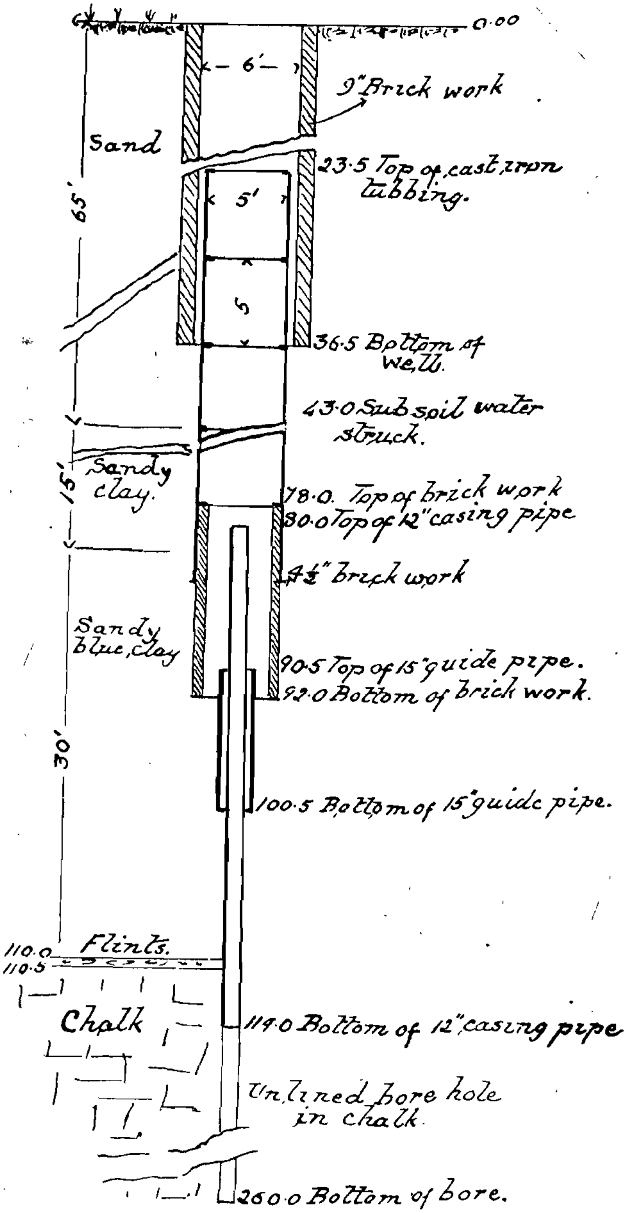
0.00
6'
9" Brick work
Sand
65'
23.5 Top of cast iron tubbing.
5'
36.5 Bottom of well.
43.0 Subsoil water struck.
15'
Sandy clay.
78.0. Top of brick work
80.0 Top of 12" casing pipe
4½" brick work
Sandy blue clay
90.5 Top of 15" guide pipe.
92.0 Bottom of brick work.
30'
100.5 Bottom of 15" guide pipe.
110.0
110.5
Flints.
Chalk
114.0 Bottom of 12" casing pipe
Unlined bore hole in chalk
260.0 Bottom of bore.

FIG. 30.

a false bottom into position. The cutting edge is driven into the water-bearing rock, and the annular space between the cylinder and the soil grouted with cement.

At the artesian well of Carrieres Sous Paissy a bore-hole 24 inches in diameter was carried down to chalk at a depth of 131 feet. To prevent pollution from the Paris sewage irrigation works, an inner tube 20 inches in diameter was sunk concentrically to the bore-hole, and the annular space filled with liquid cement, in order to exclude contaminated surface water. The bore-hole, 19·68 inches diameter, was then continued, and reached a depth of 1575 feet.

64. To sum up, the source of ground water of a district is the rainfall on the district itself or the area adjacent to it, and the quantity obtainable is that of the annual rainfall less the amount lost by evaporation or retained by the soil. The usual water-bearing strata are found in the tertiary rocks composed of alternate layers of sand, clay, gravel, and loose sandstone. The upper and middle chalk are permeable almost throughout their whole mass, but they hold water like a sponge, and part with it under pressure into fissures, which are the chief sources of supply to wells sunk into chalk. In the upper chalk the beds of flint act also as passage ways for water. Those valleys down which the greatest surface flow would take place if the strata were impermeable are generally the most suitable sites for locating wells in chalk formation. The lower chalk is not so permeable as the upper and the middle chalk, but contains "Smashes" or fractures or ruptures in which water from the upper chalk may be stored. The quantity of water in sandstone is governed by the cubic content of the interspaces between the grains, and in coarse grits may amount to 12 inches of the annual rainfall (in the British Isles). The upper and lower new red sandstones are also water-bearing formations, except the red marl found in the new red sandstone. These formations contain more water than chalk, but wells sunk in them are chiefly supplied by fissures. Green sand varies in permeability, and in a loose condition acts like sand, and is subject to blows if the "critical" velocity is exceeded (*vide* Chap. X.). In carboniferous and magnesium limestones, oolites and chalk, the passage of water is exceedingly slow, but it is effectively filtered, except where open spaces follow lines of joints and faults, and constitute natural channels through which water flows freely, but without the purification surface streams undergo from the action of sunlight. When porous rocks of different characters are separated by their beds

of impermeable material, it is often possible to obtain several classes of water from one well.

Where wells are pumped at the same daily rate without abstracting the water of cistonage the hardness diminishes during the first year and remains constant, but it increases temporarily if the pumps are lowered until the additional area drawn upon is exhausted of soluble salt. Faults in porous rock are no obstacles to the passage of ground water, except when the strata are overlaid by a bed of impermeable material in which case the fissures may become silted up, forming a natural puddle trench; in places near the sea this may result in salt water ultimately replacing fresh.

CHAPTER X.

PERCOLATION WELLS.

65. In the theoretical treatment of the flow of water into a *percolation* well, as shown in paragraph 54, the following conditions are assumed, viz. that the flow into the well is radial, and that the entry of water into the well is free, that is, the flow into the well encounters no resistance of entry through the well steining, that is, the water passes as easily through the well steining as through the soil. This is not usually the case where percolation wells are sunk into recent alluvial deposits, such as beds of shingle, sand, loam, etc., which have not consolidated, and a lining or steining of some sort is necessary. The steining generally consists of a cylinder of masonry sunk into the soil, which, in the case of wells for a public water supply, must be impermeable in order to prevent pollution from surface water (par. 63). Wells for irrigation sometimes have weep-holes in the steining, or the lower portion of the steining is built with rings of brick or stone set dry alternating with rings of masonry. The water-bearing soil being usually of considerable greater depth than the well, the bulk of the supply rises vertically upwards through the soil at the bottom of the well.

Where an ample supply of water is required, percolation wells are usually sunk into beds of gravel or sand or into sandy soil, and the amount of water a well in such soil can yield depends, if the well steining is more or less impermeable, on the area of sand exposed at the bottom of the well, that is, the discharge or yield that can be obtained from the well depends on the internal diameter of the well cylinder, and the critical discharge per square foot area of the sand, which latter depends on the effective size and specific gravity of the sand.

The critical discharge per square foot area of the sand is that produced by an infiltration head which causes a velocity sufficient just not to move or "blow" the sand into the well. This head is called the "critical head"; if this head is exceeded sand is blown into the well, and if the same quantity of water is being pumped from the well sand will continue to be drawn into the well, until the well is filled with sand to such a depth that no greater supply than the critical discharge can be drawn from the well. If, in order to obtain a greater supply, the sand is dredged out of the well, and the overtaxing continues, the well will again be filled with sand, and in time, if this process continues, a large cavity will be formed in the sub-soil, and either the earth round the well will collapse, or the masonry cylinder will sink bodily. Therefore, from a percolation well sunk into sandy soil it is impossible to obtain more than a certain definite discharge, whatever the depth to which the cylinder is sunk, and any attempt to get more than this discharge will endanger the stability of the well. Various devices have been tried to overcome the sand blows, sometimes a depth of 3 to 4 feet of broken stone is placed at the bottom of a well to weigh down the sand, but this has only given temporary relief, as in a short time the sand is drawn up through the interstices of the stone, and the "plug," as it is called, soon gets choked. As will be shown later, the maximum velocity of entry under the steining is at the inside rim of the steining (*vide* par. 71). The Indian well sinkers, from long experience, are aware of this fact, and sink a cylinder of grass rolls inside the steining till the bottom of it is a foot below the well curb, the annular space between the outside of the grass cylinder, and the inside face of the steining being filled with broken stone and shingle; the surface of the sand being exposed in the centre of the well. If the sand is fine the device does not meet with success. Mr. Farrant, sometime Chief Engineer, P.W.D., Panjab, fixes the critical infiltration head for Panjab sands at from 5 to 7 feet. At the Trichinopoly Water Works, South India, the fine sand of the Cauvery river is drawn into the pumps when the pumping head exceeds 5 feet. In the case of the coarse and heavy quartz sands, the critical head is over 7 feet.

The difficulty of sand blows in percolation wells, at watering stations on Indian railways is overcome by constructing the wells of large diameter so as to reduce the velocity of entry and to obtain storage.

66. In order to obtain what may be termed the *specific vertical yield* of the soil into which a percolation well, with an impermeable steining, is sunk, so that the flow into the well is vertically upwards through the soil at the bottom of the well and not radially through the steining—

Let A be the cross-sectional area of the well in square feet;
P the rate of pumping from the well in cubic feet per hour;

h the depth the water level in the well is reduced or the infiltration head after t hours pumping.

In any short time dt the amount pumped from the well will be Pdt, and this will be equal to the volume of the reduction of water in the well Adh, together with the flow into the well during the short time dt.

If K be the specific vertical yield of the soil under a head of 1 foot in cubic feet per hour, that is, the flow into the well upwards through the soil in the bottom of the well under an infiltration head of 1 foot, the flow into the well under an infiltration head of h feet will be Kh or

$$Pdt = Adh + Khdt.$$

If H be the infiltration head or reduction of water level in the well when the rate of pumping equals the rate of flow into the well, and the water level in the well remains steady while constant pumping is in progress for a considerable period of time,

$$P = KH.$$

From which equation K can be determined, and $\frac{K}{A}$ will be the specific vertical yield of the soil per square foot sectional area of the well under an infiltration head of 1 foot.

It is obvious that $t = \frac{A}{K} \log_e \frac{H}{(H - h)}$.

Therefore, if $\frac{K}{A}$, or the specific vertical yield of the soil, and H, the infiltration head at which the rate of pumping equals the rate of inflow are known, the time t taken to reduce the water in the well to any depth h, below the original level of the ground water plane of saturation, can be ascertained. If $h = H$, t obviously becomes infinite. The above conditions hold good so long as H is less than the critical head of depression, because for greater heads the soil in the bottom of the well is disturbed and capillary flow ceases.

In the case of the investigation for a town water supply, great care must be taken that the period of pumping in the test well is carried out for a sufficient length of time in order to observe the constancy of the water level during that period. The diminution of ground water level is so slow that a long period of time elapses before there is any evidence of a definite lowering of the ground water plane of saturation in the vicinity of a well.

67. It is rarely that a continuous discharge of any magnitude can be obtained from a percolation well at a moderate head, except in the case of wells sunk in the water-bearing sandy beds of Indian rivers, or from sand beds adjacent to and periodically fed by them, or from large sandy deposits, into which streams flow, and which receive a heavy rainfall. Generally the flow from the tributary area of a well (par. 55) is so slow that a moderately powerful pump soon empties the well, or reduces the water level to the critical depression, and a much longer time is taken for the water in the well to recoup or rise to its original level when pumping ceases. A more usual way of obtaining the value of $\frac{K}{A}$ is by a recuperation test.

If H is the normal depth of water in the well before pumping operations are started, or the critical depression to which the water level of the well can be reduced to, and the well is pumped down to an infiltration head H, and then the pumping is stopped and the well allowed to recoup, the water level in the well will begin to rise, and if at the end of t hours the water level has risen to a level of h feet below the normal ground water level, in a short time dt the water level will rise a distance dh, and if, as stated above, A is the sectional area of the well, the spring flow entering the well in any short time dt will be $-\mathrm{A}dh$, the $-$ sign being used as h is decreasing. The spring flow also entering the well is also $\mathrm{K}hdt$.

$$\therefore \mathrm{K}hdt = -\mathrm{A}dh,$$

$$t = -\frac{\mathrm{A}}{\mathrm{K}} \log_e h + c,$$

when $\quad t = 0 \qquad h = \mathrm{H} \qquad \therefore \mathrm{C} = \frac{\mathrm{A}}{\mathrm{K}} \log_e \mathrm{H},$

$$\therefore t = \frac{\mathrm{A}}{\mathrm{K}} \left(\log_e \mathrm{H} - \log_e h\right) = \frac{\mathrm{A}}{\mathrm{K}} \log_e \frac{\mathrm{H}}{h},$$

and $\quad \frac{\mathrm{K}}{\mathrm{A}} = \frac{1}{t} \times \log_e \frac{\mathrm{H}}{h}.$

Therefore, while the well is recouping by observing values of h for various times t, successive values of $\frac{K}{A}$ can be obtained. If the water-bearing stratum is uniform for the depth of the well, the values of $\frac{K}{A}$ so obtained will be nearly equal, otherwise values of $\frac{K}{A}$ for the various strata passed through must be observed, and a mean value for $\frac{K}{A}$ obtained. Mr. Farrant gives values of $\frac{K}{A}$ for Panjab soils varying from $\frac{1}{2}$ to $\frac{1}{4}$ cubic foot per hour for sandy and clayey soils. For the coarser sands of the Madras Presidency $\frac{K}{A}$ is about 1 cubic foot per hour.

68. Turning again to the equation

$$Pdt = Adh + Khdt.$$

$$dt\left(h - \frac{P}{K}\right) = -\frac{A}{K}dh,$$

$$\frac{dh}{\left(h - \frac{P}{K}\right)} = -\frac{K}{A}dt,$$

$$\log_e\left(h - \frac{P}{K}\right) = -\frac{K}{A}t + \log_e c,$$

$$\left(h - \frac{P}{K}\right) = ce^{-\frac{K}{A}t}.$$

$$\text{If } h = 0 \qquad t = 0 \qquad c = -\frac{P}{K},$$

$$\therefore P = \frac{Kh}{1 - e^{-\frac{K}{A}t}}.$$

If $\frac{K}{A}$ is known, and if after any time t the water level in the well is reduced by h feet, the rate of pumping can be obtained. If H is the depth of water in the well before pumping operations are started, or the critical head of depression, and T the time taken to reduce the water level to a depth H, the total quantity pumped out of the well will be

$$PT = \frac{KH}{1 - e^{-\frac{K}{A}T}} \times T.$$

and the spring yield will be PT — AH.

In the case of recoupment, if t is the time the water rises in a well from a depth H below the original normal ground water level (before pumping operations were started), to a depth h below the same level,

$$t = \frac{A}{K} \log_e \frac{H}{h}.$$

If T is the total time of recoupment of the well to its original water level,

$$T = \frac{A}{K} \log_e \frac{H}{O},$$

which makes T infinite. Experiment shows that when a well is pumped out and allowed to recoup, the water, unless the soil is very porous, rarely rises to its original level; but by making h very small, its value varying with the nature of the soil, we can obtain a reasonably accurate value for T.

Further, $h = He^{-\frac{K}{A}t}$ which gives the recoupment curve.

69. The safe yield from a percolation well is the supply that can be drawn continuously from it without permanently lowering the ground water level, and eventually running the well dry. It is usual to make yield tests at the time the ground water plane is at its lowest level. The well is pumped out dry, or to its critical infiltration head, and allowed to recoup, then, if as stated above, P is the rate of pumping, and it takes T_1 hours to pump the well dry or to its critical head, and it takes T_2 hours for the well to recoup to nearly its original level, the total quantity pumped is PT_1, and this is the safe yield that can be expected in $T_1 + T_2$ hours. If $\frac{K}{A}$ for the soil has been ascertained from the recoupment test, and it has not been possible to ascertain P, it can be found from the formula given in 68.

Or, $$PT_1 = \frac{KH}{1 - e^{-\frac{K}{A}T_1}} \times T_1.$$

If the total time of recoupment cannot be observed,

$$T_2 = \frac{A}{K} \log_e \frac{H}{h}.$$

By making h very small compared with H, taking into consideration the nature of the soil, a reasonably accurate value of T_2 can be obtained. An example of an actual test on a well is given below.

Diameter of well, 8 feet.

Cross-sectional area A = 50·25 square feet.

Depth of well from ground level, 22 feet.

The steining is a cylinder of 9 inches, brick masonry, in fairly good condition. The bottom of the well showed moderately coarse sand (*vide* Fig. 31). The levels are reduced to heights above mean sea-level.

Yield tests were made by pumping out the water from the well and allowing it to recoup. The water level in the well could not be lowered below − 3·41 M.S.L., as the steining showed

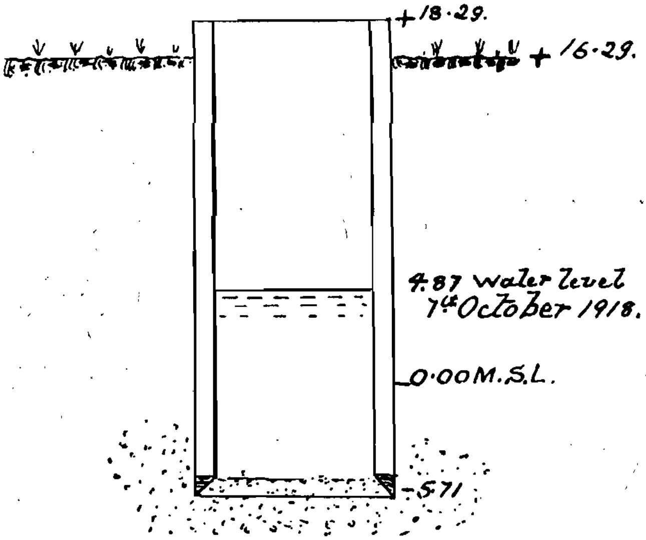

FIG. 31.

signs of bulging. The discharge from the pump was gauged over a right-angled V notch, the table below gives details of the pumping test.

The values of K in column 11 is obtained by taking a mean value of *h* during the intervals of five minutes, hence as the differences between *h* for successive intervals grows less more accurate values of K are obtained.

K for all practical purposes may be taken as 50, making $\frac{K}{A}$ or the *specific vertical yield* of the class of sand met with = 1. No tests were made of the effective size of the sand.

The well was allowed to recoup, and rose from − 3·41 at

5 h. 45 min. to – 1·41 at 6 h. $1\frac{1}{2}$ min., making $t = 0{\cdot}275$ hours. Further observations were stopped as darkness and rain set in.

$$K = \frac{A}{t}(\log_e H - \log_e h).$$

$$A = 50{\cdot}25. \qquad H = 8{\cdot}28.$$
$$t = 0{\cdot}275. \qquad h = 6{\cdot}28.$$
$$K = 50{\cdot}25. \qquad \frac{K}{A} = 1.$$

In order to estimate the time of recoupment to nearly the normal ground water plane, and for this purpose taking $h = 0{\cdot}01$, we get

$$T_2 = \frac{A}{K}(\log_e 8{\cdot}28 - \log_e 0{\cdot}01) = 6{\cdot}7 \text{ hours.}$$

1. Time P.M. H. M.	2. Water Level in the Well. M.S.L.	3. Interval.	4. Difference of Water Level. Feet.	5. Mean Head h. Feet.	6. Notch Readings in Interval. Inches.	7. Pump Discharge in Interval. Cubic Feet.	8. Capacity of Well for Interval. Cubic Feet.	9. Spring Flow during Interval. Cubic Feet.	10. Rate of Spring Flow. Cubic Feet per hour.	11. Estimated Value of K.
4.50	4·87	Five minutes.	—	—	—	—	—	—	—	—
4.55	2·87		2	1	$5\frac{1}{2}$	107·47	100·5	6·97	83·4	—
5.0	1·46		1·41	2·7	5	84·86	71·0	13·86	166·00	61
5.5	0·36		1·10	3·96	$4\frac{3}{4}$	74·42	55·28	19·14	230·00	58
5.10	– 0·54		1·90	4·96	$4\frac{1}{2}$	65·6	45·22	20·38	244·00	49
5.15	– 1·33		0·79	5·80	$4\frac{1}{2}$	65·6	39·69	25·91	311·00	54
5.20	– 1·91		0·58	6·49	$4\frac{1}{4}$	56·5	29·14	27·36	328·00	51
5.25	– 2·37		0·46	7·01	$4\frac{1}{8}$	52·0	23·10	28·90	347·00	50
5.30	– 2·77		0·40	7·44	$4\frac{1}{8}$	52·0	20·01	32·49	390·00	52
5.35	– 3·08		0·31	7·79	4	48·8	15·5	33·3	400·00	52
5.40	– 3·29		0·21	8·05	$3\frac{7}{8}$	45·0	10·55	34·5	413·00	51
5.45	– 3·41		0·12	8·22	$3\frac{3}{4}$	41·6	6·03	35·57	427·00	52

The total gauged discharge from the pump amounted to 693 cubic feet, taking T_1 as 1 hour, and $\frac{K}{A} = 1$.

The calculated discharge from the formula

$$PT_1 = \frac{KH}{1 - e^{-\frac{K}{A}T_1}} \times T_1,$$

$$K = 50,\ H = 8{\cdot}28,\ T_1 = 1, \text{ and } \frac{K}{A} = 1.$$

$$PT_1 = 658 \text{ cubic feet,}$$

which is nearly equal to the gauged discharge. Errors of observation in the depth of water on the V-notch for the different intervals of time, and the value of the assumed coefficient, may account for the difference. Assuming 693 cubic feet to be correct, the safe yield that may be expected from the well will be 693 cubic feet in 7·7 hours (i.e. $T_1 + T_2$), or 2100 cubic feet in twenty-four hours.

A test was made on the same well later in the year, when the normal ground water level was + 7·17, and the water in the well was lowered by careful pumping to − 1·93 in $1\frac{1}{2}$ hours, the quantity pumped out, as gauged over a V-notch, being 1002·92 cubic feet. The well was then allowed to recoup, and took 9 hours 17 minutes to recoup to its original level. The

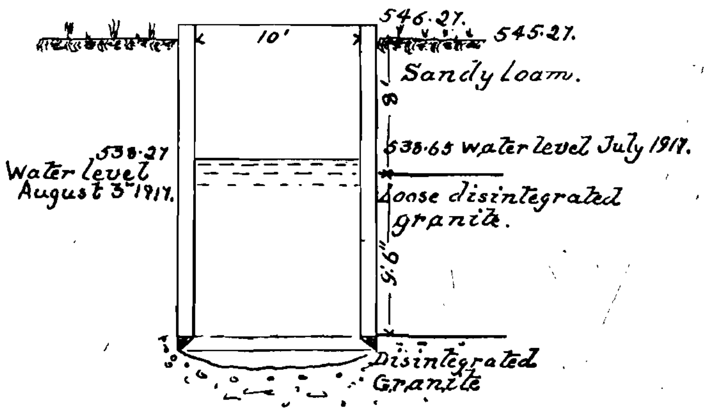

FIG. 32.

latter part of the recoupment was in darkness, and there may have been some difficulty in observing the exact level of the water.

70. This paragraph describes the analysis of an actual yield test made on an experimental well sunk into water-bearing, disintegrated, granite soil, in order to ascertain if the locality was a suitable one for obtaining a supply of water sufficient for the water supply of a small town in South India. The test well, 10 feet internal diameter, was sunk some 18 feet into the disintegrated rock, and in order to prevent pollution the steining consisted of an impermeable cylinder of masonry 2 feet in thickness. Fig. 32 shows the levels of the well and the various soils passed through. The first yield test was made on 20th July, 1917; the rest level of the ground water plane of saturation

being 538·65 M.S.L. before pumping was started. The water was pumped out of the well by a No. 6 pulsometer, and in fifty-five minutes the water level was reduced to 527·04, i.e. the well was pumped dry. The local surveyor who carried out the experiments stated that the boiler pressure was 80 lb. per square inch at starting, and fell to 70 lb. per square inch when pumping ceased. The discharge from the pump was also reported by him to be constant, giving a depth of $5\frac{1}{2}$ inches on a rectangular V-notch; the rate of pumping being estimated at 135 gallons a minute. The reduction of water level in the well for every five minutes during the pumping operations was stated to be according to the statement below:—

STATEMENT I.

Time in minutes	5	10	15	20	25	30	35	40	45	50	55
Reduction of water-level in feet	1·62	1·46	1·37	1·29	1·17	1·04	0·96	0·79	0·75	0·70	0·46

Or, the water level in the well was lowered 11·61 feet in fifty-five minutes. The well was allowed to recoup, and the water level rose from 527·37 to 536·35 in two hours and fifty-five minutes.

A second yield test was made on 3rd August, 1917, when the ground water plane of saturation was at its lowest level; the same pump being used, the water level was reduced from 538·27 to 526·69 in fifty-five minutes, *vide* statement below:—

STATEMENT II.

Time in minutes	5	10	15	20	25	30	35	40	45	50	55
Reduction of water-level in feet	1·5	1·42	1·17	1·12	1·12	1·08	1·08	0·96	0·92	0·67	0·54

The well was allowed to recoup, and the water level in the well rose from 526·98 to 535·66 in three hours and ten minutes. We have seen (par. 66) that if P is the rate of the pump discharge in cubic feet per hour, $\frac{K}{A}$ the specific vertical yield of the well in cubic feet per hour, and A the cross-sectional area of the well in square feet, and if in any time t in hours the water level in the well was reduced h feet,

$$Pdt = Adh + Khdt.$$

If we have observations showing the reduction of water level in the well or dh, for any small intervals of time dt,

$$\frac{K}{A} = \frac{1}{h}\left(\frac{P}{A} - \frac{dh}{dt}\right).$$

If there is no spring flow into the well,

$$dh = \frac{P}{A}\,dt,$$

which represents the uniform rate at which the water will fall in the well, or $\frac{P}{A}$ will represent the rate of fall in feet per hour. Statement I. can now be arranged as below :—

dt	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{12}$	Remarks.
dh	1·62	1·46	1·37	1·29	1·17	1·04	0·96	0·79	0·75	0·70	0·46	
h	1·62	3·08	4·45	5·74	6·91	7·95	8·91	9·70	10·45	11·15	11·61	
$\frac{K}{A}$*	−1·8	−0·33	0·013	0·18	0·36	0·50	0·56	0·72	0·74	0·72	0·95	* $\frac{K}{A}$ as calculated

It is obvious from the statement that the values of dh as observed for the first two intervals of five minutes are incorrect, for if, as stated by the surveyor, the pump discharged at a uniform rate of 135 gallons a minute, which in five minutes would amount to 108 cubic feet, and there was no spring flow entering into the well, the water level would have been reduced 1·375 feet, and not 1·62 feet, as recorded by the surveyor. It is probable that at the commencement of pumping the discharge was greater than that given by the surveyor, and grew less as the boiler pressure fell. It is also possible that the depths on the V-notch were not observed with that close accuracy so necessary in all scientific observations.

Turning to the recoupment test, the water level rose from 527·37 to 536·35, or 9 feet in two hours and fifty-five minutes, the rest water level being 538·65. Using the formula

$$\frac{K}{A} = \frac{1}{t} \log_e \frac{H}{h}$$

$$H = 11{\cdot}28,\ h = 2{\cdot}30,\ t = 2{\cdot}92,\ \frac{K}{A} = 0{\cdot}54.$$

In Statement II. there is the same error, viz. that the rate of reduction of water level in the well for the first two intervals of time is greater than that given by a pump discharging at the rate of 135 gallons a minute. Taking the second recoupment test, the water level in the well rose from 526·96 to 535·66 in three hours and ten minutes. Using the same formula, $\frac{K}{A} = 0{\cdot}46$.

The mean of the two experiments give the value $\frac{K}{A}$ for the soil $= 0{\cdot}5$.

Assuming $\frac{K}{A} = \frac{1}{2}$, and A for the well 10 feet internal diameter $= 78{\cdot}54$ square feet. In the first experiment the well was reduced 11·61 feet in fifty-five minutes, or 0·9166 hour.

$$P = \frac{Kh}{1 - e^{-\frac{K}{A}t}},$$

$$h = 11{\cdot}61,\ t = 0{\cdot}9166,\ A = 78{\cdot}54, \text{ and } \frac{K}{A} = 0{\cdot}5.$$

$$\therefore P = 1240 \text{ cubic feet per hour.}$$

The rate of pumping given by the surveyor works out to 1296 cubic feet per hour. Allowing for errors of observation, the calculated discharge is probably a more correct mean. The time of total recoupment is given by the formula

$$t = \frac{A}{K} \log_e \frac{H}{h},$$

$H = 11{\cdot}29$, $\frac{A}{K} = 2$. And assuming h for distintegrated granite as 0·1,

$$t = 9\tfrac{1}{2} \text{ hours.}$$

The time occupied in pumping may be taken as $\frac{11}{12}$ hours. The safe yield from the well will therefore be $\frac{11}{12}$ of $1240 = 1137$ cubic feet in 10·4 hours—say 1140 cubic feet in $10\frac{1}{2}$ hours, or 25,992, say 26,000 cubic feet in twenty-four hours.

In the equation $P\,dt = A\,dh + Kh\,dt$,

$$dh = \left(\frac{P - Kh}{A}\right)dt.$$

dh is a maximum when $h = 0$ and there is no spring flow into the well. $dh = 0$ when $P = Kh$, or when the rate of pumping

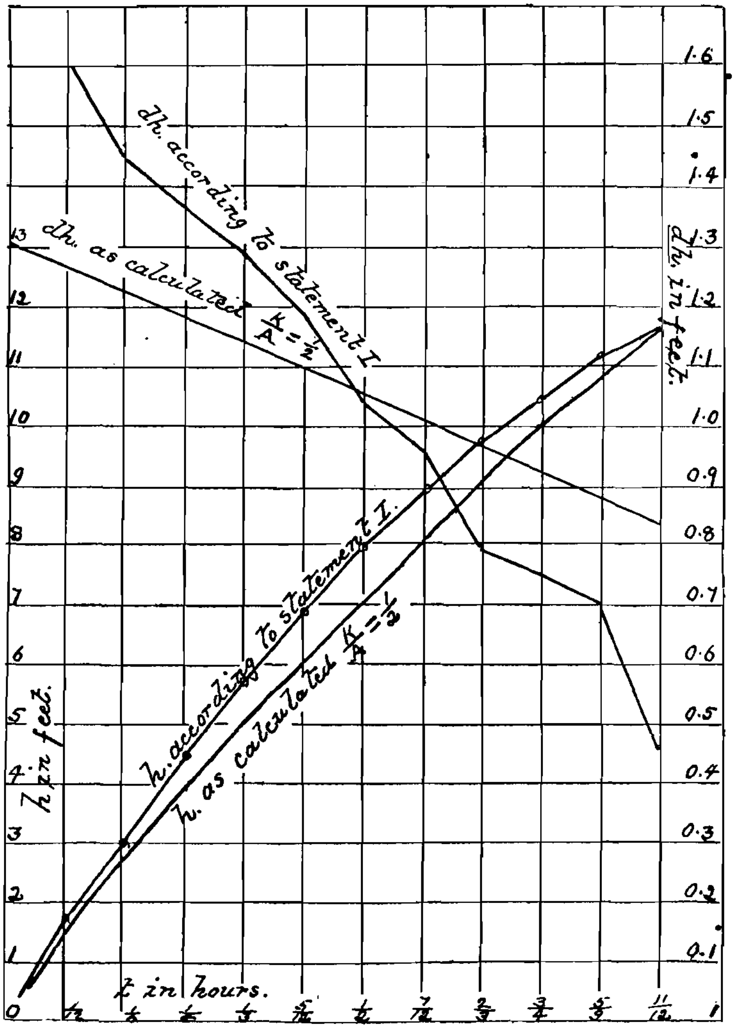

FIG. 33.

equals the rate of inflow into the well, and there is no further reduction of water level in the well.

Also, $$h = \frac{P}{K}(1 - e^{-\frac{K}{A}t}),$$

and h is a maximum when $t = \infty$ and $\frac{P}{K}$ is the maximum value of h, that is, when the spring flow into the well equals the rate of pumping, and no further reduction of water level takes place in the well.

Assuming P as 1240 cubic feet per hour, and $\frac{K}{A}$ as $\frac{1}{2}$, values

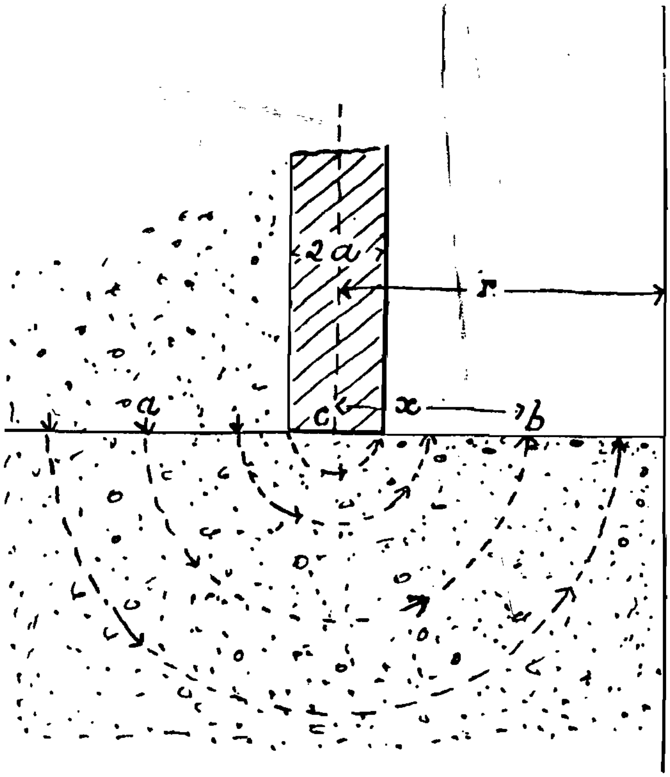

FIG. 34.

of h and dh are calculated for intervals of five minutes, or $\frac{1}{12}$ of an hour, and compared with that given in Statement I. (*vide* Fig. 33).

From the above analysis it is apparent that there is a wide field open for the investigation of the water-yielding capacities of localities. $\frac{K}{A}$, or the specific vertical yield of a water-bearing stratum, can be ascertained by sinking pipes, of convenient diameter and to the required depth, into the water-bearing stratum, pumping or baling the water out of the pipe and noting the time of recoupment.

71. The case of a well with a steining consisting of an impermeable cylinder of masonry, sunk into homogeneous water-bearing soil of some depth, may also be treated in the following manner. If r is the radius of the well to the centre of the steining, $2a$ the thickness of the steining, the flow into the well will take the line of least resistance, and the lines of flow for all practical purposes may be represented by arcs of concentric circles, as shown in Fig. 34. If h is the infiltration head, the velocity along any line of flow ab, at a distance x from the centre of the steining, will be $\frac{\mathrm{M}h}{\pi x}$, where M is the modulus or transmission constant of the soil (*vide* par. 23). This M must not be compared with $\frac{\mathrm{K}}{\mathrm{A}}$. The flow along any tube ab will be $\frac{\mathrm{M}h}{\pi x}dx$.

The flow into any circle concentric to O will be $2\pi(r - x)\frac{\mathrm{M}h}{\pi x}dx$, and the total flow into the well will be $2\mathrm{M}h\left\{r \log_e \frac{r}{a} - (r - a)\right\}$. It will be seen that the velocity of entry into the well is $\frac{\mathrm{M}h}{\pi x}$, and this is a maximum when $x = a$; or the maximum velocity of entry is at the inside rim of the steining (*vide* par. 65).

CHAPTER XI.

"MOTA" OR CAVITY WELLS.

72. In alluvial soil, where a stratum of a sufficient depth of clay overlies water-bearing sand, a "Mota" or cavity well can be installed. The masonry cylinder forming the well steining must be impermeable, and must be sunk into the clay to a sufficient depth to make a watertight joint. If the cylinder has passed through a stratum of water-bearing sand overlying the clay, all leaks under the well curb must be carefully stopped up, so as to prevent any inflow of sand into the well. The inside diameter of the cylinder should be of sufficient size to receive the pumping or baling apparatus, and to contain the sand brought up by the pipe or borehole. When the masonry cylinder has been well bedded into the clay, and the curb made as watertight as possible, a pipe is driven through the clay to the underlying water-bearing sand stratum. As soon as the pipe is clear of the clay and reaches the water-bearing sand, the head of water drives water mixed with sand up the borehole and into the well. Sometimes there is such a rush of water that the men working in the well get drenched before they can escape. The sand is cleared out of the well, and the water pumped or baled out of the well, when the water rushing in from the water-bearing sand stratum below again fills the well with sand and water. This operation is repeated until the inrushing water ceases to bring sand along with it, when the well is ready for use.

The removal of the sand from the water-bearing stratum below the clay must cause a cavity under the clay bed, just below the borehole; therefore, so long as the velocity of the water flowing through the sand into the cavity is, at any point of the sand surface of the cavity, greater than the velocity of the critical discharge per square foot area of the sand, the cavity must continue to enlarge, and the sand displaced will be carried up into the well. The function of the cavity is, therefore, to provide an area of sand sufficiently large to reduce the velocity of flow to a point at which the critical discharge per square foot area of the sand is not exceeded. Fig. 35 explains the principle of the "Mota" well. The pipe at its lower extremity should not project into, but should be flush with the clay, and at its upper extremity should not project more than 2 feet into the well. The depth of the cavity will be greatest at the centre,

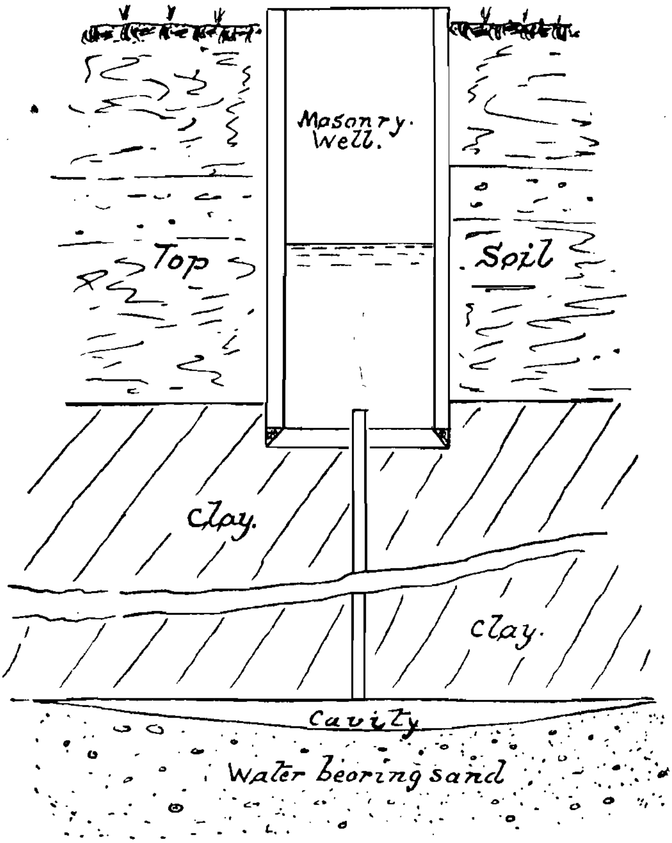

FIG. 35.

gradually diminishing to nothing where the sand meets the clay roof. The maximum depth for a cavity of large size will scarcely be 1 foot, the average depth being about 3 inches. It will be thus seen that, given the conditions for constructing a cavity or "Mota" well, a greater quantity of water can be obtained from it than from a percolation well of the same diameter. The supply is also independent of the diameter of the well. A diameter of 7 feet is required for manipulating the mote, or leather baling bucket, and assuming that a cavity has been formed by the removal of 230 cubic feet of sand, and assuming that the shape of the cavity is circular and average depth to be 3 inches, the diameter of the cavity will be about 34 feet. A "Mota" well, therefore, of 7 feet diameter would be equivalent to a percolation well of 34 feet in diameter.

The conditions necessary for a cavity or "Mota" well are that there must be a layer of clay or other firm impervious substance of sufficient strength to bear the weight of the masonry cylinder and roof in the cavity in the sand below. For a cultivator's well the layer of clay must not be of such great thickness as to make the cost of boring prohibitive for ordinary irrigation wells. The water pressure in the water-bearing sand stratum tapped must be sufficient to force the sand and water into the well.

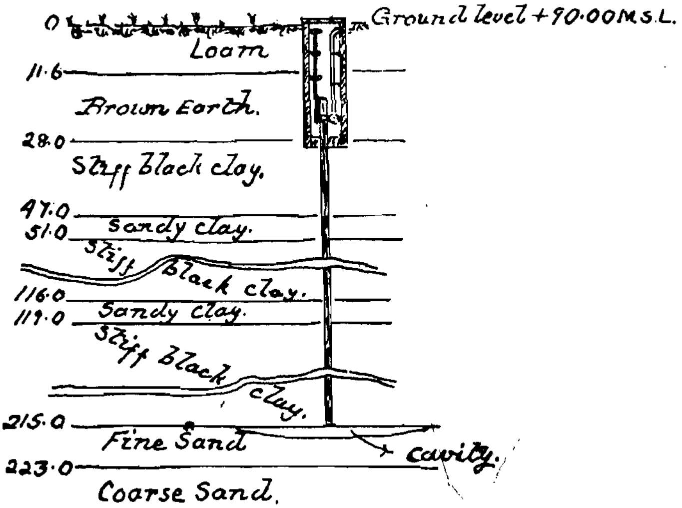

FIG. 36.

For ordinary depths the head required is—

(1) 10 feet to obtain velocity in the tube or borehole to move the sand, and to give the required discharge.
(2) 5 feet depth in the well for the leathern bucket or baling apparatus to work in.
(3) 3 feet for fluctuations in the ground water level.

That is, the normal depth of water in the well should be about 18 feet. The pipe should be of such a diameter as to reduce friction to an economical limit, and the projection of the pipe into the well should not be so high as to reduce the head requisite to give the water, flowing up the pipe, the necessary *velocity sufficient to move the sand and form the cavity.*

If a cavity or "Mota" well begins to yield a diminished supply, it is due either to the general lowering of the ground

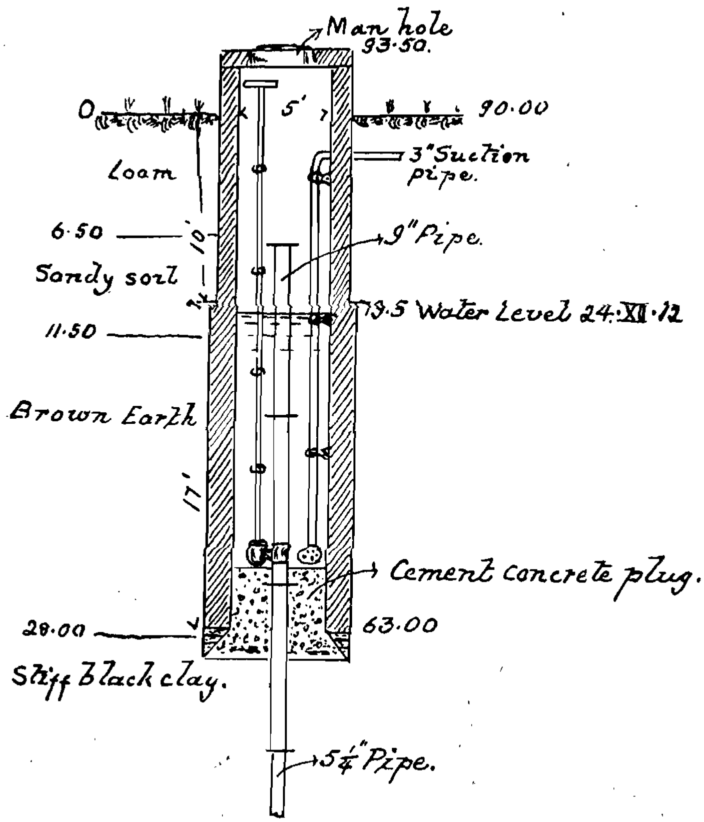

FIG. 37.

water plane of saturation in the locality, or the choking up of the bottom of the well and the borehole. The rubbish should be cleared out, and if sand is found at the bottom of the well, there is possibly a leak between the well curb and the clay foundation, or a crack or hole in the masonry cylinder, which allows sand from the layers above the clay to percolate into the well. This can be remedied by plugging the curb or repairing the cylinder. The sand in the well may also be due to the subsidence of the clay foundation, when the defect becomes serious and requires skill and ingenuity in overcoming the difficulty.

73. The example described below shows how the cavity principle was applied in the case of a deep borehole in order to obtain a supply of potable water for a small town in South India, the surface and sub-soil water being contaminated. The locality was the flat alluvial delta of the Canvery river. A

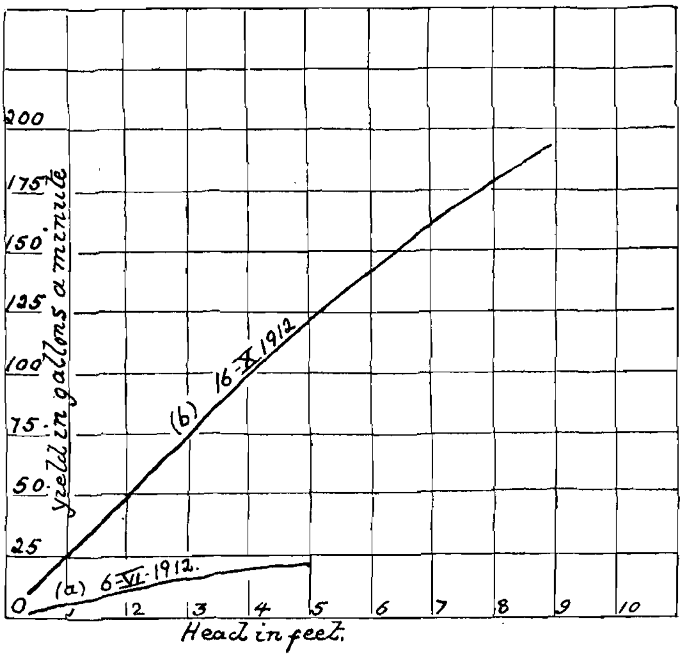

FIG. 38.

borehole $5\frac{1}{4}$ inches internal diameter was sunk through alluvial clay to the sandy strata below; the geological section is shown in Fig. 36. The $5\frac{1}{4}$-inch pipe was sunk into the sandy strata below depth 215 feet, and was then raised so as to be flush with the bottom of the stiff black clay, or at 215 feet below ground level. A masonry well 6 feet in diameter was sunk round the borehole to a depth of 28 feet, and lined on the inside with a steel cylinder to exclude sub-soil water, and a watertight joint was made between the pipe and the inside of the well by a plug of cement concrete. In order to facilitate the clearing out of the well, a saddle branch 4 inches in diameter, fitted into a valve, was fixed to the bore-pipe 2 feet 6 inches above the concrete plug (Fig. 37). The cavity was formed by first closing the valve on the saddle branch and pumping the well dry. The valve was then opened, and water and sand rushed into the well. The valve was then closed, the water pumped out of the well, and the sand cleared out. The operation was repeated until 68½ cubic feet of sand was removed. The curve (*a*) (Fig. 38) shows a yield test made on July 6th, 1912, before the sand was removed, and the curve (*b*) shows a yield test made on 16th October, 1912, after 68½ cubic feet of sand was removed.

CHAPTER XII.

TUBE WELLS.

74. In recent alluvial deposits the ground water does not flow along underground fissures or conduits, but percolates along through beds of permeable material which have been laid down by running water. Most of our large rivers rise in hilly or mountainous country; high up in its course among the hills, where the river flows with torrential velocity, it tears away earth, sand, stones, and boulders from its bed and banks, and carries them along to the plains. Where the river debouches out of the hills into the plains the velocity of its current is checked, the river is no longer able to transport the material which it holds in suspension, or rolls along its bed, and it deposits the heavy material chiefly along its sides and at its concave bends. As the course of the river in its valley wanders from side to side, it leaves behind it broad flats or terraces of alluvial soil, which are at first overflowed periodically when the river is in flood, but eventually by successive deposits rise above the flood level of the river; or the land rises, and the river carves out a new valley, leaving its original bed, as broken banks or terraces alongside its new valley. The end of a river is usually the sea, to which it transports, and in which it deposits its finer sediments, forming new land, which is being continually pushed seaward, thus forming the delta of the river. As a rule, the gradient of a river diminishes towards its mouth, consequently the velocity of its flood water continues to diminish as it leaves its source, causing the coarser material to be deposited in the upper reaches of the river, and the finer material is carried down and deposited lower down its course, or ultimately deposited in the sea. Accordingly, we may expect to find that the sub-soil in the alluvial plains near the hills contains boulders, pebbles, or coarse sand, whereas at a distance from the hills the deposit will generally consist of alternate layers of fine sand and clay. At the delta, where the finest material is deposited, clay will predominate. Owing to the strong current in the river channel

itself, the bed of the river channels of most large rivers, even in their deltaic zones, are composed of sand, often extending to a considerable depth, the texture of the sand depending on the rock formation of the country the river drains.

75. In prospecting for a water supply from wells the coarseness of the sub-soil will be an indication that the material was deposited when the river was flowing at a comparatively considerable velocity, consequently beds of clay are not likely to be found interstratified with the sand, while lower down the alluvial valley the fine sand met with in the sub-soil is an indication that beds of clay are possibly interstratified with the sand. As we approach the deltaic zone clay is more in evidence, and strata of sand are not often struck, except at considerable depths. In the great Indo-Gangetic plain in which the alluvial deposits extend to great depth, beds of clay interstratified with sand are not generally found in the upper reaches of the Indus and the Ganges; while lower down their valleys beds of clay interstratified with sand, are found. A striking evidence of these conditions is that in the Punjab the local cultivator uses a percolation well as his source of water for irrigation, while lower down the valleys of the Ganges and the Indus the local cultivator endeavours to ascertain by boring whether he can obtain conditions for the installation of a "Mota" well (Chapter IX.). As pointed out by Mr. Malony, even if the local cultivator in the Punjab did strike a stratum of clay in sinking his well, not having seen or experienced the possibilities of a "Mota" well, he would not be alive to the advantages of the clay stratum overlying the sand, and would probably sink his percolation well through the clay to the sand stratum below. Mr. Malony states that from the river Sutlege to Behar, except in the sub-mountain districts, the "Mota" well is practical, also in the alluvial tracts of Guzerat; while owing to the coarseness of the sand in the sub-soil in the Punjab, west of the Sutlege, percolation wells generally obtain ("Manual of Irrigation Wells," United Provinces, India).

76. As already pointed out (65), it is impossible to obtain from a percolation well sunk into sandy soil more than a definite discharge, whatever the depth to which the steining, if impermeable, is sunk, and any attempt to obtain more than the critical discharge endangers the stability of the well. Also, once the critical head is exceeded and the sand disturbed, it is easily moved by a head less than the critical head. Sand so disturbed takes considerable time to consolidate again. The critical discharge per square foot area of sand depends on its coarseness

and its specific gravity. If from a yield test the specific vertical yield, or $\frac{K}{A}$ of a stratum of water-bearing sand into which it is proposed to sink a well is found to be $= \frac{1}{2}$, and the critical head is observed to be 7 feet, then the critical discharge per square foot area of the well will be 3·5 cubic feet per hour. If a cultivator requires 350 cubic feet per hour, then the sectional area of his well will have to be 100 square feet, or diameter about 12 feet. If $\frac{K}{A}$ for the stratum is found to be $\frac{1}{4}$ cubic foot per hour, and the critical head 5 feet, owing to the sand being finer, a well of about 19 feet diameter will be required.

Many attempts have been made to overcome the difficulty of sand blows. It has been shown that the *maximum velocity of entry into a* percolation well is at the inner rim of the steining (par. 71), and this is the weak spot, as the sand under *the well curb may be moved, when* the velocity in the centre of the well has not reached the critical velocity. If a more or less imper*meable cylinder of wood or iron is sunk inside the masonry steining,* leaving an annular space of about 9 inches between the ma*sonry steining and the subsidiary* well, a portion of the flow is diverted from passing under the subsidiary cylinder, and the risk of undermining is less. As shown (par. 23), *the effect of a partial obstruction is to increase* the head necessary to produce flow; the effect, therefore, of contracting the area at x (Fig. 39) will be to reduce the velocity of flow at the well curb, and the well can be worked to a greater *head than would be otherwise possible, until the critical head in* the subsidiary well is reached.

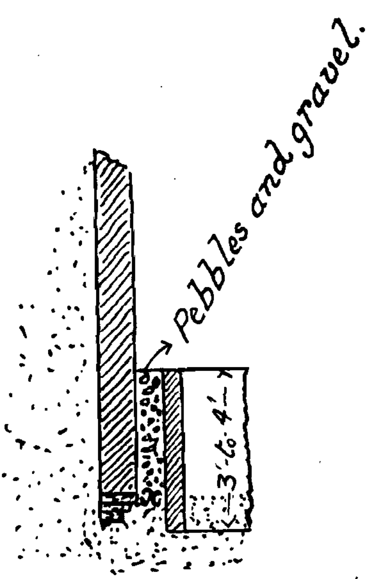

FIG. 39.

77. Another method is to construct the well steining with open joints, pervious to flow, and to plug the bottom of the well with a layer of concrete, *so that all flow into the well is* radial. If the openings in the steining are sufficiently small or close enough to keep out fine sand, the well will have to extend

for a considerable depth into the water-bearing soil, or be of considerable diameter, in order to obtain the necessary area for an adequate supply of water. Where the water-bearing soil is of great depth, a tube well can generally be installed with success.

In a tube well the flow into the well is radial, through a strainer of such dimensions that all but the finest sand is kept out of the tube, the required area of discharge being obtained by the length of the tube. The lower end of the tube is closed so that no flow comes vertically upwards through the bottom of the tube. In sinking a tube well an ordinary or casing pipe, of such an internal diameter that the tube well strainer with its joints can easily pass through it, is first sunk to the required depth into the water-bearing soil; it is advisable to sink the casing pipe to a slightly greater depth than that required for the strainer, in order to allow for any rise of sand into the casing pipe when it is finally settled. The casing pipe should be allowed to stand for some days to permit the sand to consolidate, and then should be sludged clean. The tube well strainer with its connecting pipe is then lowered into the casing pipe and held suspended at its correct depth, while the casing pipe is removed, leaving the tube well strainer embedded in the sand. The supply from a tube well is considerably greater than from an ordinary percolation well, so that tube wells are generally used in conjunction with pumps, the strainer being connected directly to the pump suction, or by an intermediate length of plain pipe. A tube well may, however, lead into a masonry sump to enable leather buckets, or other methods of raising water, to be used. The sump must be sunk well below the rest water level in the pipe, in order to obtain the required head; and in order to prevent sand blows into the well, as the critical head is generally exceeded in tube wells, the floor of the sump must be made water-tight by a concrete plug of suitable thickness, the pipe connecting the strainer with the sump well passing through the concrete.

Where there is a great depth of water-bearing sandy soil, a tube well properly constructed enables large quantities of water to be drawn from the sandy soil without drawing away the sand thereby causing cavitation and subsidence of the soil. For such a purpose the strainer must be strong enough to resist the pressure of the soil surrounding it at a considerable depth. It must exclude all but the finest sand, and be so made that grains of sand cannot choke it, and prevent admission of water. It must be strong enough to stand reasonable handling before and during the process of sinking. It must be durable and maintain its efficiency under any pumping conditions. The joints between the successive lengths of the strainer must be strong, easily made, sand-proof, and allow a slight flexibility in the strainer.

The discharge from a tube well depends on the nature of the water-bearing soil into which it is sunk, and on the length of the strainer. The resistances to flow into the tube well are—

(1) Resistance of entry.

(2) Loss of head necessary to produce velocity in the tube.

(3) Frictional resistance of the tube.

It is obvious the greater the infiltration head the greater will be the velocity of entry, and hence the greater the resistance of entry. Mr. Brownlie fixes the economic head at 7 feet for a 5-inch tube, and 14 feet for a 10-inch tube, in Panjab sands. He states that the actual velocity of entry should not exceed $\frac{1}{2}$ inch per second, and that in Amritsar sand (Panjab) it is not economical to obtain more than 2 cusecs per tube; he gives the following figures for tube wells sunk in Panjab sands under favourable conditions (Panjab Engineering Congress) :—

Internal diameter of strainer tube, ins.	$3\frac{1}{2}$	5	5	7	7	9
Length of strainer, feet . . .	34	42	54	54	74	95
Discharge cusecs	0·25	0·5	0·75	1·0	1·25	2

Tube wells vary in design from a strainer of perforated vitrified pipe inserted into a casing pipe of somewhat larger diameter, the annular space being then filled with gravel and the casing pipe then removed, to the Ashford patent tube well, where the strainer consists of a framework of bars round which copper wire is wound at high tension, through steel rollers, giving the wire a wedged-like shape in section, so that when in use the wire presents a flat surface to the water-bearing soil surrounding it, with a slit between adjacent strands of $\frac{1}{100}$ inch in width. The casing pipes are standard casing tubes with swelled and cressed joints.

The statement below gives the dimensions of strainer and casing pipes :—

Nominal diameter of tube well strainer, inches . . .	3	5	7	10	12	14
Size of casing pipe, $\frac{\text{O/D inches}}{\text{Thickness}}$	$\frac{5}{8\text{ w.g.}}$	$\frac{7\frac{1}{2}}{6\text{ w.g.}}$	$\frac{9\frac{1}{2}}{5\text{ w.g.}}$	$\frac{12\frac{1}{2}}{\frac{9}{32}''}$	$\frac{14\frac{5}{8}}{\frac{5}{16}''}$	$\frac{16\frac{5}{8}}{\frac{5}{16}''}$
Size of pump suction pipe connected to the strainer tube. $\frac{\text{O/D inches}}{\text{Thickness}}$ . . .	$\frac{3\frac{1}{2}}{10\text{ w.g.}}$	$\frac{5\frac{1}{2}}{7\text{ w.g.}}$	$\frac{7\frac{1}{2}}{6\text{ w.g.}}$	$\frac{10\frac{1}{2}}{\frac{1}{4}''}$	$\frac{12\frac{1}{2}}{\frac{9}{32}''}$	$\frac{14\frac{5}{8}}{\frac{5}{16}''}$

Mr. Ashford fixes the length of strainer as 150 times the diameter of the tube. He also states that when starting a tube well it is advisable to at once apply the maximum infiltration head by pumping to the full capacity of the well. This action washes out the finer sand and clay from the zone surrounding the strainer, and cleans it for its work. If this cannot be done without drawing in coarse sand, a smaller gauge strainer must be used (Panjab Engineering Conference, 1918). Heads of up to 20 feet have been applied to the Ashford tube wells without harm.

The statement below shows the discharge under favourable conditions from the Ashford tube wells sunk into Panjab sands :—

Nominal diameter of strainer in inches .	3	5	5	5	7	7	7	10	10	10
Length of strainer, feet .	—	35	50	100	50	75	100	50	100	120
Discharge cusecs . .	—	0·33	0·5	0·9	0·65	1	1·12	1·0	1·8	2
Brake horse-power for an average lift of 30 feet .	—	$2\frac{2}{3}$	$3\frac{1}{2}$	$6\frac{1}{4}$	$4\frac{1}{2}$	7	$8\frac{1}{2}$	7	$12\frac{1}{4}$	14

Mr. Farrant, from experiments made by him with a tube well $4\frac{1}{2}$ inches in diameter, and strainer 30 feet long, closed at its lower extremity, and pumped to a head of 12 feet, found the discharge to be $K_r \times h$. Where K_r is the transmission constant for radial flow as distinguished from K for vertical flow (*vide* par. 66), and h the infiltration head, $K_r h$ being in cubic feet per hour. For the well in question K_r was observed to be 72 cubic feet per hour, when $h = 1$ foot. The area of the strainer was about 35 square feet so that $\frac{Kr}{A} = 2$ for Panjab sand. For vertical flow $\frac{K}{A} = \frac{1}{2}$ so that one tube well is equivalent to four masonry wells, but as a tube well can be pumped to a greater head than a masonry well, the advantages are considerably on the side of the tube well, if there is a sufficient depth of water-bearing sandy soil to warrant its installation.

It is obvious that a tube well can only be installed where there is a considerable depth of water-bearing sand, and, economically, where the water-bearing strata is at a comparatively moderate depth below the surface. In some cases it may be necessary to penetrate several strata of impermeable soil before a stratum of sufficient depth of water-bearing sand is obtained. If the cost and difficulty of boring increases with the depth, it may be more economical to install a " Mota " well, if there be a stratum of clay overlying the water-bearing sand. Where there is doubt as to the nature of the sub-soil, it will usually be advisable to put down trial bore-holes, and from the data thus acquired an estimate can be formed of the probable water yield and the cost of a well of the size necessary to give the quantity of water desired. Should the well pass through unproductive clay belts of any considerable thickness, the cost may be reduced by the introduction of plain pipes between the lengths of strainer pipes at the points where these clay belts occur. In the case of Fig. 24 the strainer would only require to be of the length a, or equal to the depth of the water-bearing stratum; and in Fig. 23, if h is the infiltration head necessary to produce the required discharge, the length of the strainer need be only $H - h$ in length, and the rest of the well be a plain pipe. If a centrifugal pump is employed, which is the usual practice when the permanent rest water level does not exceed 30 feet below the surface, the pump should be set not more than 10 feet above the permanent rest water level, and preferably only 5 or 6 feet, as the rapid pumping operations possible with the Ashford strainer may reduce the water level in the neighbourhood of the strainer by 10 or 15 feet.

78. We have seen in paragraph 54 that

$$c_1 \log_e x = My + c_2,$$

$$c_1 \log_e D = MH + c_2.$$

$$\therefore c_1 \log_e \frac{D}{x} = (H - y)M \text{ and } c_1 \log_e \frac{D}{r} = \mathbf{M}\boldsymbol{h},$$

$$\therefore H - y = \frac{h \log_e \frac{D}{x}}{\log_e \frac{D}{r}},$$

which gives the equation to the curve of the cone of depletion. D is generally assumed to be from 600 to 1000 feet when equilibrium is established. The curve depends on the head required to produce a definite discharge, and is not dependent on M or the nature of the water-bearing stratum. Mr. Brownlie states that from observations made by him on the cone of depletion of tube wells under a head of 7 feet, he obtained the following results :—

Depth of cone of depletion,	50	feet from	well	=	3·25	feet.
,, ,, ,,	100	,,	,,	=	2·00	,,
,, ,, ,,	230	,,	,,	=	1·00	,,

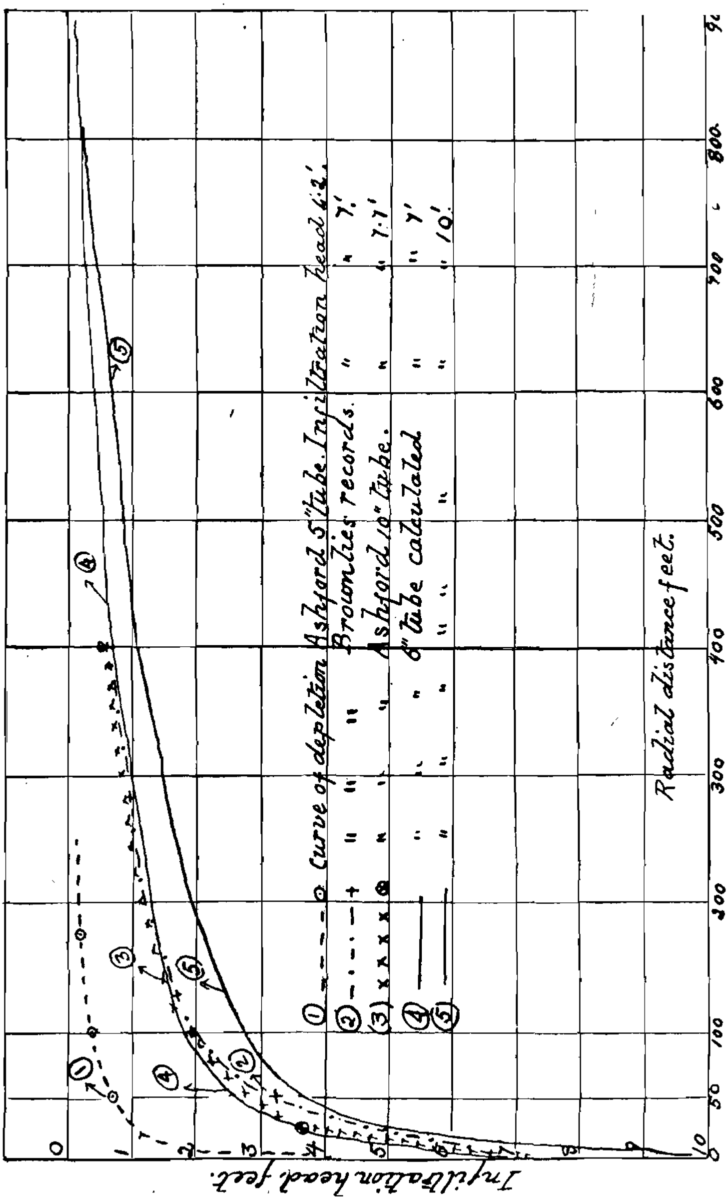
① Curve of depletion Ashford 5" tube. Infiltration head 6.2'.
② Brownlies records. 7'.
③ Ashford 10" tube. 7.1'
④ 6" tube calculated 7'
⑤ 10'.
Radial distance feet.
Infiltration head feet.
0 1 2 3 4 5 6 7 8 9 10
0 50 100 200 300 400 500 600 700 800 900

FIG. 40.

For a head of 10 feet the cone of depletion merged into that for a head of 7 feet at 500 feet from the well, where the depth below the normal ground water plane was 0·75 feet. In an Ashford 5-inch tube well, with a depletion head of 4·2 feet and discharge 0·28 cusecs, at 50 feet, the depth of the cone of depletion was 0·7 feet; 0·4 at 100 feet; and 0·2 at 175 feet from the well. In a 10-inch tube, depletion head 7·7 feet, discharge 1·93 cusecs, the depths of the cone of depletion were: At 25 feet from the well, 3·7 feet; at 125 feet, 1·7 feet; and at 400 feet, 0·7 feet. In the gravel beds on the left bank of the Rhine, near Langen Erlen, in a well boring, the limit of the cone of depletion for an

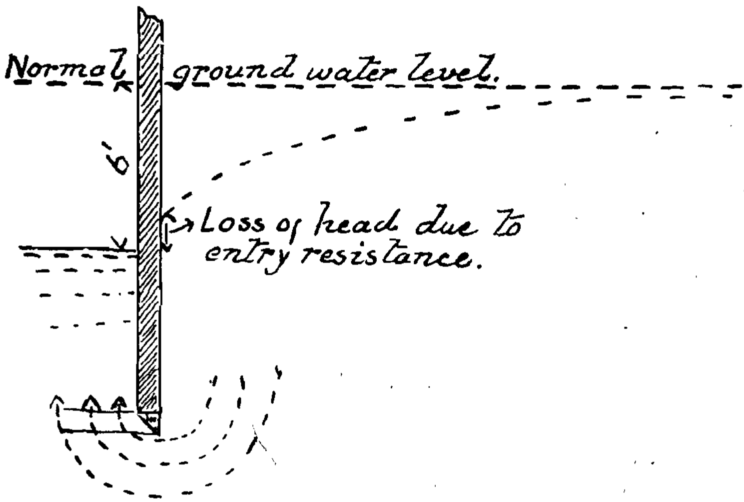

FIG. 41.

infiltration or depletion head of 7·88 feet was 273 yards, or 819 feet. Fig. 40 shows the above limits of the cones of depletion and two curves of the curve of the cone of depletion for a 6-inch tube well, calculated from the formula—

$$H - y = h \times \frac{\log_e \frac{D}{x}}{\log_e \frac{D}{r}}$$

for values of h of 7 and 10 feet; value of D = 1000 feet.

Mr. Brownlie also points out that in an ordinary percolation well, with an impermeable steining, 100 square feet sectional area of well, and yielding 2000 gallons an hour, under a head of

6 feet, at a distance of 50 feet from the well the depth of the cone of depletion was only $\frac{1}{2}$ foot. As the cone of depletion depends on the amount of water abstracted from the soil, and as in this case the flow of water through the soil is first downwards and then upwards vertically into the well, under the well curb, the loss of head due to the resistance of entry must be appreciable, so that the head inside the well required to give a discharge equal to that flowing towards the well is greater than the head outside the well required to overcome the resistance to flow in the soil (*vide* Fig. 41).

79. A simple form of tube well is the Norton or Drive tube well, which consists of a perforated tube with a toughened driving-point. The tube is driven into the soil by a weight slung from a derrick, additional pipes being added as the pipe goes down. A pump is fitted to the last pipe, and by this means a small quantity of water is obtained. Should pure water be required, the pipe is driven through the upper water-bearing stratum, through impermeable strata to a lower water-bearing sub-stratum. For ordinary pumps the average lift should not exceed 20 feet.

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