INDIAN ENGINEERING

RELATING TO

IRRIGATION, WATER SUPPLY OF TOWNS, ROADS AND BUILDINGS

BY

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PREFACE.

THE chapters which form this book are a revision of articles which originally appeared in *Indian Engineering* of Calcutta and are now reproduced by the kind permission of the Editor of that Journal. They are based upon my larger books, but the treatment of the subjects discussed differs from that previously adopted. Each of these topics is here dealt with inclusively by itself, and, when necessary, are added brief descriptions of how constructed works give effect to the principles stated. In my former books each class of construction is separately described, and the way in which principles affect it is thereafter noted. This book is mainly concerned with the principles governing design and construction ; these fundamentals are therefore explained more fully than before, and works are alluded to only generally. Although Indian conditions are taken into account, the principles described are of world-wide application and I thus trust the book may be of extended use ; as it is shorter and cheaper than my previous publications, I hope it will be of wider service.

W. L. STRANGE.

WORTHING,
27th January, 1923.

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INDIAN ENGINEERING.

CHAPTER I.

INTRODUCTORY.

In the following pages the chief matters that are discussed relate to principles, which being unalterable, govern design, although the way in which constructed works give effect to them may vary. If the engineer grasps these principles and applies them properly, he will build his works on sound foundations and may rest assured of their success. Mathematics, formulæ, tables, and statistics have not been included, for, although they are necessarily required by a designer, they are given in many standard books: nor for the same reason have particular constructed works been described. All of these are of great importance, as they constitute the technical and structural equipment of the profession, and without a knowledge of them it cannot be practised with confidence, for in these advanced days the rule of thumb methods, which formerly were relied on, must now give place to the teachings of science and experience.

Irrigation is dealt with chiefly, because it involves many principles; some of these are also applicable to most of the other branches of engineering treated, while they, in their turn, are of use to the irrigation engineer who should know something of them —this explains the combination of all four main subjects in a single book. The irrigation engineer is concerned with large natural forces, which although variable, act under laws that must be obeyed, and applies them for the benefit of man. It is only reasonable that he should study Nature and take her as a guide; this is emphasised at some length, and examples are given of success or failure according as she was followed or flouted. Dr. M. O. Foster, in his presidential address to the Section of Chemistry of the 1921 meeting of the British Association, remarked—" Nature ignored or misunderstood was the enemy of man ; Nature studied and controlled was his friend." To interpret Nature it is necessary to understand her operations, and this can be done only after making careful observations. Lord Kelvin (then Sir William Thomson), (p. 20) when presiding over the British Association in 1871, urged that experimental research ought to be made an object of national concern, and not left to the " private enterprise of self-sacrificing amateurs." The recommendation for States to establish hydrographic surveys is in accordance with this advice. The engineer must have a correct knowledge of the quantity of water with which he has to deal, in order that he may design properly his works for storage, flood disposal and distribution, and he will best gain it from the data furnished to him by the expert hydrographic surveyor.

Particular stress is laid on the determination of high-flood discharge, which if not disposed of safely, may cause great damage. Many engineers place great reliance on formulæ for such discharge, but these are generally defective as almost all of them treat the whole catchment as uniform and apply to it a highly variable coefficient, the selection of which really begs the question. A formula which does not take into account all the factors which it should comprise is neither theoretically correct nor practically sound, and may be misleading. The strong recommendation made is to divide catchments into component parts, throughout each of which the conditions are practically uniform, and to obtain, from scientifically observed areas, correct coefficients for each factor of discharge, and to apply the results thus ascertained to the similarly treated gathering grounds of contemplated schemes. The flood discharge depends as much upon the nature of the ground as on the character of the rainfall ; its rate therefore varies with each catchment, and should preferably be determined by gauging.

The duty of water is discussed, and the duty of the engineer is several times alluded to—all who are devoted to their profession will recognise its call, as fully as did Nelson's seamen, and will give of their best. It is probable that few Indian engineers have studied the legal aspect of water, considerations as to which are dealt with in one of the chapters. They, fortunately, have to carry out their works in a country where sound irrigation law has been based on the slowly-accumulated experience of centuries. New countries which have to gain their own experience, may well take Indian wisdom as a guide in order to avoid difficulties that may otherwise occur. Certain financial matters are examined; the principles laid down have particular force in these days when both labour and capital demand high rates of remuneration. Various physical effects—such as seepage, hydraulic gradients, silting—have their principles explained, and the way these influence construction is illustrated by examples drawn from practice. The main points which should be attended to in the design and construction of large schemes and of certain of their constituent parts are noticed. The maintenance of a careful record of the history of important projects is advised.

In dealing with water supply, the requirements of a small non-manufacturing town of, say, 20,000 inhabitants in a rural area are chiefly borne in mind. The East is peculiarly subject to the ravages of waterborne diseases, to prevent which good water supply is the only effectual remedy; thus its provision is a highly desirable sanitary improvement. Unfortunately the cost involved is considerable; when a town is poor, it is recommended, on the principle of half a loaf being better than no bread, that the cheapest types of works should first be constructed, and that superior ones should be substituted for them as the prosperity of the community increases. Such development is likely to follow the construction of a water-works project; as it occurs, greater individual demand for water is sure to take place, and both of these factors will aid in financing the improvement of the original scheme. No doubt State assistance will be given in deserving cases, for an organised water supply is a national asset, seeing how an infected town may become the centre of widespread disease. A storage reservoir is advocated as generally the best source of supply because of its described advantages: the water can at first be led from it in an open channel to tail settling and coagulating basins, and thence to distribution mains, from which it can be drawn at distributing cisterns. This is the most rudimentary project practicable, and superior arrangements necessary for its development are detailed. Town water supply and irrigation schemes have much in common in regard to supply and consumption but differ in distribution.

Roads are first discussed with reference to the part they take in promoting communication in a country. They originally formed the only internal lines for travel and traffic, were afterwards greatly superseded by railways in highly civilised countries, but they are again asserting their utility owing to the advent of motor vehicles. They are the cheapest means of opening up a new country, and without their lateral aid a railway will not make its influence widely felt. The classes of roads in respect to their functions, and with regard to their construction, are mentioned, and the main considerations governing the design and formation of a good roadway are described. Matters in connection with cross-drainage works are noted : they also affect irrigation works of similar nature.

Buildings are treated shortly in connection with their general aspects. Houses will have to be constructed by engineers who deal primarily with irrigation, water supply, or roads, and they are therefore recommended to acquaint themselves with the leading architectural principles, which, if followed, will make their structures possess the beauty due to truthful construction and suitability, and secure comfort and economy.

PART I. IRRIGATION.

CHAPTER II.

GENERAL PRINCIPLES.

IRRIGATION is the art and practice of supplying water artificially to land to secure or increase the growth of crops. The art consists of engineering, the practice of agriculture, and the two should work hand in hand. Plants require for their growth proper conditions of heat, light (actinic rays) and moisture. In irrigating countries the first two are abundant, but the last one is frequently deficient, and is the only one which can be supplemented on a large scale, and that is effected by irrigation. Rainfall is the sole source of water supply, but as it often occurs irregularly, and occasionally at unseasonable times, especially in tropical and sub-tropical countries (where the need of moisture is enhanced by the great heat), its deficiencies there have to be made good by irrigation. In temperate climates the rainfall is more evenly distributed and more regular, while the heat is moderate, so that in them is little necessity for irrigation and more for its opposite—drainage.

Irrigation confers many benefits ; it aids general development by utilising the valuable national asset of the water available ; it increases the food supply of the country, and thus enriches the cultivators, the prosperity of whom profits other sections of the community ; indirectly it increases railway receipts and trade generally, and reduces poverty, disease and crime ; in countries liable to famine it is the best preventive of scarcity, and works for its extension are the most suitable for the employment of workers who then have to be relieved ; in semi-civilised lands it turns turbulent and non-productive peoples into peaceful and industrious ones. It is not possible to assess the money value of all these indirect benefits, but it is certain they are a substantial addition to the assets of the State, which profits thereby in a manner not possible for a commercial undertaking that can take credit only for direct cash receipts. While irrigated crops are more valuable than unirrigated ones, the difference in out-turn is not solely due to the means of irrigation, as the former also require better soil and cultivation and suitable climate, but still irrigation alone allows full advantage to be received from these favourable conditions. Taking everything into consideration, it may be said that if an irrigation work eventually pays for all its working expenses, including interest on its capital cost, it will have justified its construction, by increasing the assets of the State and the prosperity of the people. It is not conducive to progress to condemn a scheme because it is not more lucrative. The direct profits from irrigation schemes will seldom be attractive to commercial enterprise, on account of their small amount and the long time which must lapse before they are realised, owing to the slow growth of irrigation. The State, however, can be content with a low rate of profit slowly attained, seeing that it gains by its indirect receipts from irrigation.

The quantity of water available for irrigation is extremely variable, as it is increased by rainfall and seepage, and is diminished by evaporation and absorption. To obtain the greatest advantage from it the former should be utilised to the fullest extent and the latter lessened as far as practicable. As rainfall is the original source of supply and varies greatly, its amount will be the principal controlling factor, and as the supply from artificial works generally alters with it, the issue of that for irrigation has to be regulated accordingly. Thus distribution to the irrigators has usually to be effected, not by fixed quantities, but by varying shares of the fluctuating amount available. This establishes the principle of co-operation, making all realise that they have interests in common and will not eventually benefit if instead they study only their own individual requirements. Another great principle is that economy in consumption should always be practised : in bad seasons it has perforce to be observed, and that it may then be most effective, the irrigators should be accustomed to it always : in good seasons it will permit of an extension of the irrigated area, and thereby will add to the prosperity of the cultivators and to the wealth of the country. While such economy is thus a general benefit, it is also a particular one to the individual, for a lavish use of water may injure the crops— by leaching the manure and natural fertilising constituents out of the land ; by water-logging the soil, thus souring it by depriving it of aeration ; and also by causing injury to the crops by bringing up subsoil alkaline salts to the surface by capillarity.

There are several methods of irrigation. The most important of these is flow irrigation, which takes place when water can be delivered by gravitation to the irrigable lands ; the largest areas are thus served by reservoirs and canals. Its cost is the least to the irrigator, while as large areas can be concentrated, the expenses due to maintenance and supervision are reduced. Its disadvantage is that it may lead to excessive use of water, to diminish which the engineer must devise proper arrangements for distribution and enforce them by his supervision. Lift irrigation is practised where the water has to be raised artificially on to the land : it is very expensive in time and labour to the irrigator, but because of this, induces great economy in consumption. Flood irrigation consists in diverting river floods on to lands above the ordinary level of supply and soaking them thoroughly, thus enabling crops to be grown on the flooded area. Inundation irrigation takes advantage of the high rise of large alluvial rivers above the country which slopes gently from them, having thus been formed by the previous deposit of their silt. The flow thereby made available, both by its quantity and its silt content, converts practically rainless areas, which would otherwise be deserts, into extremely fertile ones. Well irrigation is a particular form of lift irrigation, and has many advantages, the principal of which are that it makes the irrigator his own master, utilises water which would otherwise flow underground to waste, and by lowering the plane of subsoil saturation decreases the tendency to water-logging. Sub-irrigation is conducted by means of a system of underground pipes conveying the water below the ground surface, and thus reducing loss by absorption and practically eliminating that by evaporation. It is very expensive, and as it wets only the cold subsoil and does not sufficiently moisten the warm surface soil, rich in bacterial life, it does not produce heavy crops. " Dry farming " may be said to be the negative of irrigation : in it crops are grown when the rainfall is scanty by continuously preserving a good surface tilth by cultivation, whereby evaporation is greatly reduced : it is much more costly in labour than irrigation, and yields light crops. The lessons it has for the irrigator are the economies of supply resulting from controlling evaporation and avoiding lavish use of water. The main principles of irrigation apply to all these methods, and effect can be given to them in most cases by the individual irrigator, but only by the engineer, in co-operation with him, on the large schemes under flow irrigation.

On such large schemes the first matter to which the engineer has to attend is the quantity of water available naturally, or which has to be secured artificially. A correct knowledge of this quantity is essential for the proper design of works for storage, flood disposal and distribution, and to acquire it dependence should not be placed on formulæ and assumptions, but on actual observations of Nature's operations, which should, within reason, be numerous and prolonged so as to gain a thorough knowledge of her vagaries. Next, he has to elaborate his scheme, which should be adapted to the social, economic and physical conditions that exist, and this he should do in collaboration with the revenue officer and the agricultural expert. When all preliminaries have thus been settled, he should translate his abstract proposals into concrete constructions by the execution of his project, and doing his best to gain security for his works and the confidence of the irrigators by the sufficiency of their supply. He will remember that soundness of construction is essential, as the works will have to withstand the unceasing action of water, day and night, year after year, and he will not forget that he has to deal with not very enterprising agriculturists, who have neither the means nor the inclination to run risks with their cultivation. Lastly, he has to maintain his works in continuous efficiency, and to encourage the growth of irrigation by sympathetic management.

Irrigation has to be administered under legal provisions, which should be adapted to the simple community which will conduct it ; this is especially the case in eastern countries where it will chiefly be practised. The principal objects to be secured by an irrigation law are :—conformity with physical, social and political conditions ; clear and precise definitions and prescriptions of all general matters ; elasticity to meet varying conditions in minor matters ; and sufficiently deterrent penalties for all wilful breaches of the law. In regard to procedure the law should provide for the prompt settlement of all engineering matters without recourse to the courts ; the avoidance of expensive litigation, as far as practicable, by local enquiry and arbitration ; and the simplification of legal procedure when litigation is unavoidable. Wherever irrigation is long-established, it should be carried out in general accordance with old custom, with such improvements as will not conflict with that, or will be agreed to by the irrigators. In newly irrigated countries the engineer has first to determine on engineering grounds the extent and priority of the water rights, existing or prospective, and to submit his report to the administrator, who should pass his order thereon, which should be subject to appeal to the courts within a prescribed time. A water right confirmed by both administrative and legal authority is practically unassailable, and experience shows that it will seldom be contested.

Irrigation can be assisted by the State in the case of private works by loans for their construction, improvement or extension, the loans being repayable with interest in a term of years, so that they will not be a final charge against the community. In regard to commercial enterprise, assistance can be given by concessions of land on favourable terms ; loans at small interest ; remission for many years of tax assessments on increased valuations due to irrigation ; guarantees of interest on capital invested ; and aid in the construction of the works, etc. The greatest help to irrigation, especially in the East, is the construction, maintenance and management of public systems which are generally large. In India hitherto commercial enterprise in irrigation has not been successful, but may become so under the newly altered political conditions. Aid has there been given to private agriculturists with very good results and will no doubt be continued. The great development of irrigation in India has been by the construction, maintenance and management of Government schemes by the Irrigation Department : these comprise all varieties and sizes of works, some of which are the finest in existence anywhere, and these irrigate a total area much in excess of that of any other country. These State works are on the whole remunerative and successful in general improvement, and are standing monuments of what can be effected by wise and just administration of schemes designed, constructed and controlled by expert engineers.

CHAPTER III.

NATURE AS GUIDE.

ENGINEERING has been defined to be the art of directing the great sources of power in Nature for the use and convenience of Man : that being admitted, it seems obvious that the engineer should go to Nature for guidance. He should recognise, however, that, as she is lavish in her operations (for she conducts them on a grand scale with limitless resources), he must perforce adapt his contrivances to his restricted means. He should acknowledge also that she works in accordance with laws which he too must obey to gain success, for if he acts in conflict with them, he will fail. History shows what great results have followed the intelligent appreciation of the hints given by Nature—Newton[1] observing the fall of an apple was led to the discovery of the laws of gravitation ; Watts, after studying a boiling kettle, laid the foundation of the science of steam ; Galileo, when nineteen years old, gazing at a swinging lamp in Pisa cathedral, found out the law of the pendulum for the measurement of time ; and Franklin, from watching the lightning flash, started the harnessing of electricity. The sailor, following the kingfisher, which poises itself in the air to detect its prey and then plunges into the water to secure it, has located the submerged hostile submarine by observation from an aeroplane and destroyed it by bombs. The soldier, noting the diversified colouring of animals to secure invisibility, by copying Nature has shielded his guns from observation. The airman, seeing that all flying creatures from the eagle to the gnat are heavier than air and overcome the drag of gravitation by their high power, has developed the aeroplane. Of all professions that of the irrigation engineer benefits much by the study of Nature's operations and a few instances of this are given below.

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[1] For Newton's monument in Westminster Abbey, Pope wrote a Latin inscription ending with these lines in English (which, however, were not reproduced thereon)—

> Nature and Nature's Laws lay hid in night :
> God said, *Let Newton be !* and all was light.

To determine the maximum discharge of the floods of which his works have to dispose is one of the most difficult problems the engineer has to solve. To aid him certain of his ingenious fellows have devised formulæ for this purpose, but as each of these contains a highly varying coefficient, for which an adoption has to be made from the results of experience, the help does not go very far, and may be misleading. A cognate science to hydrology, is meteorology, but the meteorologist does not depend upon formulæ. He recognises that " the essence[1] of science is measurement, and the problem for meteorology, as for every other science, is to discover what to measure and how to measure it. . . . The limited predictions of meteorology are based on an immense number of observations." The results of these observations are noted on charts, and to enable a forecast to be made, successive charts are compared with one another. The charts which the irrigation engineer should prepare in this connection are the records of actual flood observations. The more observations he makes, the greater will be his ascertainment of facts, for Nature takes all factors of discharge accurately into account and presents the actual resulting flood as the correct solution of the problem. If, however, a deduction has to be made from rainfall observations, it should be recollected that the run-off depends upon the physical characteristics of the catchment as well as upon the precipitation on it. As those generally vary in most catchments which have to be dealt with, the recommendation made (p. 47) is not to treat the whole areas as uniform, but to sub-divide them into constitutent parts for each of which the conditions are the same throughout. If numerous observations of selected minor areas are made by trained investigators, it may be possible to arrive at co-efficients to be applied for every factor of discharge to catchments newly under examination and similarly subdivided.

In regard to the yield from tropical catchments it is believed that no formula has been devised, and resort has accordingly to be made to stream gaugings. Where the time of observation is limited, a comparison of the concurrent record of the area under investigation with that of a similar one for which gaugings have been made for a long period will be of use, and the same remark applies to the determination of high-flood discharge. If yield has to be estimated from rainfall observations (p. 41) a similar recommendation to that for high-flood discharge is made (p. 45)

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[1] *The Nation and Athenæum*, of July 23rd, 1921, Vol. XXIX., No. 17, page 626.

—namely that the whole catchment should not be considered to be the unit, but should be subdivided into minor parts, each with uniform conditions throughout its extent. Nature treats each of these differently and sums up the contributions of each minor area to give the total yield of the catchment.

When forming the layers of an earthen embankment the engineer should note the effects of stratification in Nature. Rankine ("Civil Engineering," eleventh edition, p. 318) points out—"The stability of sedimentary rocks in the side of a cutting is greater when the beds are horizontal, or dip away from the cutting, than when they dip towards it." Thus the embankment will have the least tendency to slip outwards when its layers are slightly sloped downwards from each face of the dam, as they will, on the contrary, then have an inclination to move inwards to the centre line, and thus to compress the earthwork and make it more solid and watertight. Conversely, if a retaining wall has to be freed from earth pressure, its backing should be formed in layers gently sloping downwards away from it. Against an abutment, or wingwall, the layers of a canal bank should slope a little downwards towards them, so as to secure a watertight connection with them during and after settlement. Natural hills and hillocks generally do not have an even slope but one that varies from steepness at the top to flatness at the bottom. Similarly, the engineer designs very high earthen dams with slopes gradually flattened from the crest to the base.

A water cushion is an instance of how Man takes a hint from Nature and applies it differently. Below a waterfall the overflow scoops out a basin, the extent of which depends upon all the natural conditions of amount of discharge, height of overfall, depth of tail water and character of the channel, and thus prevents further erosion. To excavate a large pool in hard material would be expensive, so the engineer obtains a protecting cushion of water, when the foundations of his work require it, by building a weir wall downstream of them so as to form a pool, and he designs that with regard to the same natural conditions. Where a stream has to descend quickly from a high to a low level down a hard slope, it usually fashions its bed with a rough surface, so as thereby to diminish the velocity of its flow and deliver that gently at the bottom. If, however, the surface is left smooth, the discharge acquires great velocity, and thus much erosive power, and this is resisted at the end of the descent by the formation of a pool. The engineer provides for such great changes of level by rough-pitched rapids, or aprons below masonry works, and protects their toes by tail works to stop erosion downstream.

Nature reclaims lands by the deposition of silt, consisting usually of light, small grains : in the upper reaches of an alluvial river these are suspended in supernatant overflows and the heavy coarse detritus rolls along the bed to fill its depressions ; only the finest mud therefore is passed on to the surface of the delta which is thus raised by true alluvium. Man imitates this process by warping, or colmatage, utilising muddy overflows for the purpose. The engineer endeavours to pass on nothing but the finest silt to fertilise the irrigable lands, by admitting only the surface flow of rivers into his canals, and to exclude the infertile bed silt by silt traps at his weirs, or to get rid of it along his canal heads by escapes. To make his task easier he locates his weirs where the water is naturally quiescent, for if he chooses sites where it is in violent flow, and the heavy silt is thus distributed throughout it, he is only inviting trouble. The basins of weir backwaters and the beds and side slopes of canals are waterproofed by the deposit of fine silt : the engineer, when necessary, hastens the process by throwing in fine earth upstream. He strengthens his canals where they pass through low lands by setting back the banks so that silt may be deposited on the berms thus formed.

In a delta the courses of the branches of the river are often changed by overflow from neighbouring channels. This, although of use in equalising the raising of the land there, shows the advisability, in ordinary circumstances, of making each part of an irrigation system independent of the others. Nature, when her conditions are settled, preserves her drainage systems similarly independent of others.

In alluvial country the natural heads of inundation canals, those of branch canals and of water courses led therefrom, frequently start with an upstream direction. This, apparently, is due to a deposit of silt on the upstream side of the off-take, due to the change of direction of the inflowing water there (causing retardation of velocity), and by erosion by swirls on the downstream side thereof. When a new head has to be made for such a canal, it seems advisable similarly to point it a little upstream so as thus to diminish the inflow of heavy bed silt, as that will thereby be swept past it.

At a cut-off in an alluvial river violent changes of course take place downstream. Sharp curves are at once produced and upstream of them are at first left projecting banks which produce swirls and still greater erosion. Gradually the projections are worn away and the river assumes gentler curves and thus gains a stable condition, as the water flows along these with but small erosive action. Originally, engineers endeavoured to protect danger points by the construction of spurs, but these, like the natural projecting banks, caused swirls and increased erosion which eventually destroyed them. The " impregnable head " of the Bell bund avoids this disaster by following Nature : it is formed with a curve, the radius and extent of which are adjusted to the natural conditions of river velocity and composition of the river section, as evidenced by existing river curves upstream. Thus the current glides past it without erosive action and the work remains as a permanent protection.

The *mota* well of the United Provinces (p. 99) depends for its action on the way Nature forms a crater, with a large circular horizontal top, in the sand underlying the vertical shaft up which water is drawn ; this reduces the velocity of entry and thereby prevents sand passing into or choking the well. Modern tube wells, on the contrary, have their inlet perforations in the vertical sides of the tubes, so that craters cannot form alongside them, and sand is thus carried into them unless they are protected by efficient strainers. By inserting in a well shaft horizontal adit pipes, bored with holes along their beds, craters should be formed below these apertures which will act similarly to, although much smaller than, those which are produced underneath the shafts of *mota* wells.

CHAPTER IV.

OBSERVATIONS.

PROGRESS in all scientific professions depends greatly upon correct observations, and engineering, which has been defined as the art of directing the great sources of power in Nature for the use and convenience of Man, benefits much from them. In old days, when the conditions to be satisfied were easier than they now are, much good work was doubtless done with little theoretical preparation, but that time has now passed and the rule-of-thumb engineer will easily be distanced by his scientific contemporary. The earlier works may in this respect be considered to be pioneer experiments, pointing the way in which development should be attained and mistakes should be avoided. The modern engineer should, therefore, not despise his predecessors, but rather should appreciate their courage in venturing on new designs and forms of construction, and their skill in meeting the difficulties which confronted them. He should realise that all science is progressive and should take as his guide the experience of the past as modified by subsequent knowledge. Such knowledge will chiefly be acquired by observations of natural causes, which will indicate the nature and extent of the forces that have to be met, and should suggest the best method of dealing with them.

In regard to observations the most important consideration is that they should be accurate, for, otherwise, they will be misleading and may cause undue expense, or even danger. Next, they should be carefully recorded in such detail that they will explain how they were made, so that they can be utilised in the future, although the data thus made available may be applied differently, should this become necessary by the development of science. Then within reason they should be numerous, so as to obtain true averages, and where great variations may occur in the phenomena dealt with, they should be prolonged so as to take all such changes into account. In such cases a few isolated observations may not be truly representative of the natural conditions, and will then occasion error. Most observations should be of a practical nature so that they may be utilised directly by engineers. At the same time what may at first seem to be only matters of theoretical interest should not necessarily be discarded from study as they may form the bases of important discoveries. This is notably the case in electrical development but also holds good in irrigation. For example, in the hydrographic survey of a large alluvial river it is desirable to include the whole of the course within the limits under investigation, for changes may occur in the lengths where there are no irrigation works which will affect the sections where such exist. If economy has to be practised, it is, however, preferable to reduce the number of the stations to those which can be dealt with by highly-paid skilled observers than to have numerous observations made by lowly-paid indifferent men, so that dependable results may be secured.

An observer should not be content with the mere production of tabular figured statements. He has presumably made a careful study of them, and in the course of this has, doubtless, come to certain conclusions, or interpretations, which might escape the notice of a casual reader of his figures. By clearly giving his opinions, as well as the facts on which they are founded, he will not only record his own ideas but may suggest to others trains of thought which may produce more correct inferences. Every scientific investigator should regard himself as one of a band of professional brothers, intent on adding to the general store of knowledge, and not as striving for his own personal distinction. Much good will result if both facts and opinions are contributed to professional journals, or as technical papers.

A complete list of the different kinds of observations which are of interest to the irrigation engineer would be a lengthy one, so that only a few of the more important are briefly noticed below. (p. 20.)

Rainfall.—The effect of large natural features on precipitating or diverting the rain ; the variation in gauged measurement due to different heights above ground of the top of the receiving funnel ; the maximum intensity of rainfall and its duration as measured by automatic rain gauges.

Yield of catchments as influenced by their surface and subsoil conditions, and by the character of the rainfall.

High-flood discharge as similarly affected by the catchment and rainfall ; also by the configuration of the gathering ground and its general position with respect to the direction of storms.

Rate of flood travel due to the nature of the course of the stream and of its longitudinal and cross sections; the effect on it of tributary inflow and of the direction of storms.

Seepage as modified by the nature of the subsoil; the effect on it of deep-seated channels and of surface irrigation; its amount and rate of flow; the nature of the matters dissolved in it.

Water-logging as dependent upon the capillarity of the subsoils and the character of the causal saturation; measures for its prevention or reduction.

Silting of reservoirs as varied by the conditions of the surface of the catchment, and the climate, including the rainfall; the amount at different periods of the monsoon; the nature and locality of the deposit; the best methods of reduction.

Percolation under dams as influenced by the depth and nature of the foundations, the amount of the water pressure and the silting of the reservoir bed.

Shrinkage of earthwork in dams as altered by their height, material and construction, so as to determine the proper allowance for settlement; the amount of vertical and horizontal settlement during and after construction, especially at the highest sections.

Hydraulic gradients of new and old earthwork and of natural soils; also of various sands on which large weirs may be constructed; the effect thereon of cut-off walls and other arrangements for lowering the gradient and retarding subsoil flow.

Rate of inflow into wells, both alluvial and non-alluvial, as modified by subsoil conditions.

Co-efficient of weir discharge.—Many experiments have been made in France, America, and elsewhere, but few have been carried out on the sections of works as constructed in India.

Co-efficients of sluice discharge.—The most modern experiments have been, and are being, carried out at the Assuan dam on the Nile. They, also, might be supplemented by ones for the sluices of different dimensions in Indian works.

Silting of channels.—The excellent experiments carried out by the late Mr. Kennedy, C.I.E., should be continued.

Alluvial rivers.—Similarly the investigations made by the late Mr. Molloy should be carried on.

Reinforced concrete.—Little is yet known of the behaviour of this material when subjected to the continuous action of water under pressure and freshly charged with air, and experiments to determine this are desirable.

The above are purely engineering investigations, but there are others which are also partly, or wholly, agricultural, such as soil and water analyses ; the useful effect of rainfall ; the determination of the duty of water under various conditions, with especial reference to economising supply and thereby increasing the irrigated area ; the most productive crops to grow and their proper rotation ; and the best seed and manure to select. Most of these will preferably be carried out at experimental stations under the management of trained observers not likely to be transferred, and these will doubtless include in their observations the actual results obtained by ordinary irrigators.

CHAPTER V.

HYDROGRAPHIC SURVEY.

To enable the irrigation engineer to design his irrigation works with confidence he should have a thorough knowledge of the amount of water with which he has to deal. On the one hand he will thus be able to utilise that amount as fully as is practicable, and to provide economically for the safe discharge of the surplussage. On the other, he will avoid the provision of inadequate or excessive storage capacity and canal or flood discharging power. He will thus make the most of his opportunities with due regard to safety and economy. Now this complete knowledge of hydrographic conditions cannot be obtained by a mere inspection of the locality as those conditions may greatly vary. It has to be acquired by prolonged and careful observation which any individual engineer may be unable to carry out, either because his other duties will not permit, or because his tenure of office may be short. The period of observation may, however, be reduced for any particular locality if there exists another area with similar hydrographic conditions which has been under observation for a considerable time, and especially if that observation has been conducted on similar lines. An observer who has devoted himself to the study of hydrographic phenomena, and has wide experience of them, is much more likely to come to correct conclusions in such a case than one whose specialised knowledge is more limited.

It has been found necessary in many scientific professions to form special services for investigation. It is doubtful if in any of these the necessity is so great as it is in irrigation engineering, for that is concerned with meteorology which is the most inexact and difficult of all sciences. This fact has been recognised in France by the constitution of the civil Hydraulic Engineering Corps which investigates and plans, while the Public Works Department carries out the construction and repair of State Works. In America elaborate series of experiments have been carried out at Lowell and elsewhere. It is questionable if in India, the premier irrigating country of the world, there exists in any Province or State a properly constituted hydrographic survey. Highly scientific work there has been left principally to individual enthusiasts, such as Kennedy and Molloy, who devoted their lives to investigations, and in consequence greatly added to the knowledge of their profession. To secure continuity and similarity of observation, it is better to have a settled organisation and to utilise in it the services of those who have shown a decided bent for carrying out purely scientific work (p. 2).

A complete hydrographic survey would necessitate a staff of directing and inspecting officers and of whole-time observers and would thus be costly. It would therefore seem advisable to commence on a smaller scale and to expand the establishment thereafter as found desirable. As a minimum there should be for each Province, or large State, a hydrographic surveyor to introduce a regular system of observation, and members of the ordinary district staff might be selected to carry out the observations under his instructions. At the commencement only a few typical stations might be established and the number of these might be increased gradually as required. The aim should be to secure from the first reliable results which would be under the control, and subject to the check, of a thoroughly trained expert who would not have to perform other duties which would prevent him from giving his undivided attention to investigation.

There are many hydrographic phenomena (p. 16) which require detailed and continuous examination, among which the following may be mentioned. In regard to rainfall—the effect of the altitude of the station and the height of the raingauge above the ground; the proper distribution of gauges as affected by the physical configuration of the ground; the periodicity, direction, and intensity of the rainfall. In respect to river flow—the amount of discharge throughout the year; the variation due to rainfall and how it takes place; the amount of turbidity in different seasons and stages. For high-flood discharge—in what degree the factors producing it came into action, and also the maximum discharge, its duration and rate of variation, and the total yield of individual storms. For reservoirs—information as to replenishment throughout the season of inflow; as to the losses by evaporation and absorption; and as to the amount and distribution of silt deposit on the bed. For canals—gauging of irrigation supplies and losses in transit; the effect on the latter of the depth of the water table and of the nature of the soil.

Then experiments are desirable on percolation and seepage to determine how these continue or decrease under settled conditions, how they increase with an extension of irrigation, and what is the rate of subsoil flow.

The above enumeration of observations is an indication that it is practically impossible to expect the ordinary district staff to carry out the large amount of scientific work involved and shows that a special staff is necessary to cope with it. Every engineer who has to deal with hydrographic problems will welcome scientific and accurate observations which will render their solution easier and make it more correct. Naturally the cost of acquiring this information will have to be considered, but as explained above this may initially be started at a low figure and increased as found desirable. The expense of the investigation is likely to be covered many times by the savings thereby effected, and the various administrations are therefore strongly urged to commence and continue it. They are doubtless aware that in India for want of scientific and accurate data mistakes involving much loss of money and reputation have occurred. They may be assured that, like other countries, the empire will benefit by acquiring reliable hydrographic statistics for utilisation in drawing up schemes for all classes of public works concerned.

CHAPTER VI.

HYDROGRAPHIC DISTRICTS.

WHEN a new country has to be prospected, or an old one to be administered, for irrigation purposes it is advisable that the principle of hydrographic districts should be borne in mind. A hydrographic district is the surface catchment area, or gathering ground, of the main stream and the tributaries thereof draining it, and its boundary is the watershed dividing it from neighbouring similar districts. The whole of the run-off of the rain falling on its area naturally reaches the point where the stream crosses its downstream boundary, except the amount lost in transit by evaporation and by absorption which is not afterwards returned by underground seepage. If, however, by artificial diversion water is abstracted from the stream, or additional supply is led into it from neighbouring gathering grounds, the district may be considered to be diminished or increased in proportion to the amount of the flow thus dealt with. Otherwise, the fall of rain on the other side of the bounding watershed has ordinarily no effect on the discharge of the district. The exception is where there is a subterranean connection with catchments the surfaces of which are beyond that watershed. Such cases are rare and occur principally in the dolomite formation, and the decrease or increase of flow is indeterminate when that is underground and unseen. Such flow may also be altered by a change in the direction of the underground discharge. This occasionally and suddenly takes place, as the result of the blocking of a subterranean channel by silting, etc., or the formation of a new course down previously dry fissures by the solution of the soluble rock which separated them from the original channel.

The principal artificial alteration of a hydrographic district consists in leading into it for irrigation additional supply from neighbouring rivers where water is running to waste and is not likely otherwise to be utilised : well known Indian examples of this are the Periyar Project in Madras and the Upper Jhelum Canal in the Punjab. Thus supplementing supply does not conflict with the principle of utilising it in a single district: it should, however, be a matter for careful consideration if the supply should be diverted from a district where it could be used for irrigation.

The size of a hydrographic district may vary from the catchment of a small stream to that of a considerable river; this gives the application of the system great flexibility and therefore adds to its value. For the sake of proper administration it is desirable to make its area of some size, and to regulate its extent in accordance with the irrigation interests involved. Thus a district which is sparsely populated and has few works should be made larger than one with many inhabitants and numerous irrigation schemes, so that each will more or less involve the same amount of professional supervision. The boundaries of a district, or series of neighbouring districts, should, as far as practicable, correspond with the existing divisions of a country, so that there may be but little overlapping of authority in different departments. In parts of India there will not be much difficulty in arranging for that as there the village boundaries are often themselves on watersheds.

The advantages of hydrographic districts are that in them irrigation interests will be similar throughout their extent. Administration will be facilitated as each can be placed under an officer who will not have to consult other engineers of his own rank when attending to his charge, regulating supply, or devising extensions of his works or new schemes. Unfortunately in many cases States are divided from each other by rivers as they form clearly marked boundaries. At the same time these rivers may furnish supply for irrigation on both banks or be utilised for navigation, and conflicting interests may thus occur among the rival inhabitants of each State. An instance of this happened about 1902 on the Helmand river between the Afghans and Persians, who instead of going to war about their dispute, wisely referred it to the Government of India for arbitration. Such difficulties would disappear if the catchment itself and not its main drainage line was treated as the political division. Unfortunately, it is practically impossible to effect changes of political boundaries between different States, but it is easy to make alterations of administrative ones in the same State.

Where an irrigation scheme is of a large size it will naturally form a hydrographic district of its own, or if it is of the first magnitude, two or more such districts or charges. The system can be developed by treating the areas connected with small works as sub-districts, each of which should, as far as practicable, be dealt with independently of others. Its ultimate development would be to make the major parts of individual schemes entirely self-inclusive. Thus it is not generally advisable that one channel should tail into another. This used to be done so that the tail of the upper channel could be made larger, as its surplus discharge could be passed on to the lower one. Now, however, it is generally held that the disadvantages in adopting such a design are great, as the tailing channel runs close to the supplied one and thus interferes with the irrigation of the area between them, and the gauging of the discharge utilised by each is difficult. Thus in respect of both large and small schemes and of irrigated tracts the principle of the hydrographic district is in conformity with the axiom that every irrigation scheme, as far as practicable, should be independent of others and be self-contained.

CHAPTER VII.

NATURE AND LEGAL ASPECT OF WATER.

IRRIGATION is the art and practice of supplying water artificially to land to secure or increase the growth of crops. The engineer has not much direct interest in land except to see that his schemes will command fertile soils, as to which he will be wise to get prior advice from agricultural experts. His main concern is with water, and here again, when necessary, he should obtain assistance from analysts to be assured that the supply he proposes to give will be beneficial to the land. In regard to the amount and duration of that supply he must rely upon himself, and by careful and prolonged observations should obtain correct data on which to base his schemes.

It is as well that the engineer should realise how the general peculiarities of water differ from those of land so that he may understand the best way of administering the use of the element with which he has to deal. From this point of view the principal characteristics of land are that it is immovable; it usually has fixed boundaries and an unvarying extent; it is unchangeable in ordinary circumstances, but when any of its constituents are artificially removed, as by mining, they will not be naturally replaced; and, lastly, in most countries it is private property. Water differs from land in all of these particulars. It has the capability of motion from one place to another; it varies in quantity from year to year, particularly in irrigating countries, being increased by rainfall and seepage, and being diminished by evaporation and absorption; thus it cannot fairly be divided between users of it in definite amounts, but must be allocated to them by shares of the fluctuating available quantity; it is not a fixed amount and irreplacable, but is an annual supply. Lastly, in the East large supplies of water are usually developed by the State, as private persons there have not the means or knowledge to utilise them. With these great differences it would appear logical to treat the possession of land and water differently.

There are two main classes of law which affect irrigation—the Civil Law and the Common Law. The Civil Law was established under the Roman Empire and was one of its most beneficent enactments. Its original application there to irrigation in later times fell into disuse, with the result that chaos followed : it was re-established by Count Cavour under King Victor Emmanuel by drastic measures, and modern Italy has benefited much by the wise and strong legislation enacted by them. Under the Civil Law water is considered to be the common property of all ; it is thus vested in the State, and cannot be made the personal property of private owners. Under it public water is not attached to private properties, nor is it controlled by riparian owners who cannot generally claim fixed rights thereto ; such can be obtained only by permit of the State, or after undisputed beneficial use continued for a long time. The principle of this law gives the State administrative control of streams, and by preventing litigation, affords security to irrigation enterprise.

By the Common Law of England water is not held to be the possession of the people, but to be attached (even in the case of public water) to riparian lands, the owners of which can demand compensation when deprived of their supply. Even there, however, administration has had to be enforced in respect of streams for sanitary measures, for navigation purposes, and for the protection of riparian owners generally. The advantage of the general public is thus not considered, and it is thus not given its natural right to a necessary element. A water-right is not assured until by litigation it has been secured against other claimants ; moreover, a decision as to ownership is liable to be attacked at any time, and may then be reversed, so that the tenure of the right is most uncertain.

The Common Law fails in this respect in treating water as a fixed private possession, like land, instead of regarding it as a very varying public property, and one that must be shared by several in order that full benefit may be obtained from it. The explanation may be that this form of law is in force chiefly in non-irrigating countries, where water is looked upon generally as a nuisance to be got rid of by drainage. In lands where irrigation is practised water is, however, considered to be the life blood of cultivation ; it is there highly prized and is made available by expensive works, generally small in the case of those constructed by private owners for private water entirely arising on their own land, but usually large when public water is utilised by the State for public benefit under the Civil Law.

The Common Law confers water-rights on riparian owners in the order of the priority in which these were acquired by them, and, as a rule, the upper proprietor has a superior claim to a lower one : the interests of the two are thus opposed to each other. In some new countries under this form of law claims have been made to water aggregating several times its actual amount, and thus cannot at any time be wholly satisfied, while in seasons of scarcity holders of late rights may be totally deprived of water. By the Civil Law all sanctioned irrigation is treated equally, and thus the irrigators have interests in common, and each has a right to his definite share of the fluctuating supply. This induces the economical use of that supply in seasons of deficiency, and at all times gives, as far as practicable, that security of tenure which is essential to the success of irrigation enterprise. These remarks apply to public water which has to be shared by many, and not to private water which is produced by the rainfall, or arises, on a single property and can be fully utilised thereon, which is thus a private possession.

Naturally an engineer will not be able to dispute as to legal technicalities; he prides himself on being a practical person and can point out with confidence the justification by actual experience for holding the views stated above. Where the Civil Law prevails, irrigation prospers by the security afforded to all sanctioned enterprise, and the most progressive irrigating countries are those which have adopted it. Where the Common Law obtains, irrigation languishes, as settled rights are essential for it. As the Common Law is relaxed and the provisions of the Civil Law are adopted, so does irrigation develop. Such is the verdict of different States in the U.S.A., and in France, Italy and Spain, all progressive countries, which, having experienced the ill-effects from a public point of view of the former law, have adopted, either partially or wholly, the latter one. Fortunately for India her public water from immemorial times has been vested in the State for the best utilisation in the general interest : it will be a bad day for her if she ever takes the retrograde step of making public water a private possession, and thus disregards her own experience of centuries.

CHAPTER VIII.

FINANCIAL MATTERS.

IN India new irrigation projects are treated as quasi-commercial schemes which must justify their construction by sufficiently favourable financial results. The way in which this is done will shortly be examined, suggestions for alterations of the existing procedure will be made, and proposals for economies in the programme of construction will be put forward. If the financial rules under which irrigation is carried out are too rigid, and do not take into account all benefits received from it, many otherwise desirable projects may be negatived and the development of the country thereby retarded. As time goes on and the most favourable systems are completed, those which can still be constructed will have less and less natural advantages, and the application to them of such financial restrictions will probably lead to their condemnation. On the contrary, if too free a hand is allowed, the general taxpayer, who furnishes the funds required for construction, may be saddled with unproductive expenditure incurred for only a section of the population. The matter should therefore be considered from both points of view, and if a reasonable compromise is practicable, effect should be given to it, so that the capital assets of the country may be increased without burdening it with unduly small revenue results.

The Capital Account of a project represents the initial cost of all the works comprised in it then in existence ; it consists mainly of debits of expenditure incurred with occasional credits for certain receipts. The debits are of two main classes—direct and indirect charges. The former includes the cost of works, establishment and tools and plant : the latter, the capitalisation of the abatement of land revenue on the areas occupied by the works, leave and pension allowances and interest on expenditure during construction. The Revenue Account on its credit side shows all direct receipts from sales of water, minor produce, etc., and on its debit side, all charges for maintenance, as none of these are written off to the Capital Account. The gross receipts from the project, less the maintenance charges debited to it, will be the profit from it, and this, reckoned on the total amount of the Capital Account, will be the percentage return on the capital expenditure incurred on the whole scheme. All this is quite correct from a purely accounts point of view, but it is not so certain that it is justified from an administrative one, and that should be considered most. The main thing noticeable is that, while the Capital Account is debited with indirect charges, the Revenue Account is not credited with indirect receipts, and thus the general account appears one-sided. Now these indirect charges amount to a very large percentage of the total cost, and may increase to 25 per cent. or more thereof if the completion of the whole scheme is delayed. Also, if the project is constructed of full size long before irrigation distribution is developed, or if the growth of irrigation is much slower than was anticipated, the revenue return will suffer. Thus the sum at charge, and the initial loss on the working of a project, may become so much swollen that it may be impossible subsequently to secure an adequate return from it, and for this reason a scheme otherwise desirable may prove a financial failure. Irrigation is essentially productive in its nature, and thus increases the assets of a country, otherwise its wealth, and this increment re-acts so as to produce still more wealth. The agricultural population with its larger spending power consequent on irrigation benefits the trading community, and the prosperity of the one leads to that of the other. Then from the purely administrative point of view other advantages accrue—railway receipts become larger; more immunity from scarcity and famine is gained, and the cost of measures of relief is *pro tanto* reduced ; impoverishment, sickness and crime, and the expense of their prevention are lessened ; and even military expenditure is curtailed when turbulent frontier tribes are turned into peaceful agriculturists. It is impossible to assess exactly the money value of all these benefits, although it can assuredly be said that it amounts to a very large sum. The suggestion put forward is that these indirect revenue benefits should be treated as a set-off to the indirect capital charges now made. It is believed that revenue officers and engineers will be in favour of it, and their views are entitled to quite as much respect as those of accountants. Moreover, it is thought that accountants themselves will admit that the rules are made to suit commercial schemes which do not get the benefit of indirect receipts, and that they are thus not applicable in this respect to projects financed by Government which do obtain that advantage. As minor matters in this connection, the opinion is hazarded that the percentage charged for establishment on large works is excessive, being based on results of the expenditure on the entire departmental staff, many of whose duties are really administrative, not engineering. Also, it may be stated that the value of all services and supplies to other departments should be fully credited to irrigation schemes, as, otherwise, the accounts do not correctly show the true costs of the different departments, and irrigation is deprived of what is justly due to it.

One of the largest items of indirect charges is the interest on expenditure during construction. It depends upon the amount of the sum at charge, the rate of interest allowed, and the time taken to construct the works. From an accounts point of view it is therefore best to defer the bulk of the expenditure as long as possible, and as soon as it is incurred, to complete the works as early as practicable and bring them at once into operation. Engineering considerations may interfere with this programme, but if they do not, effect should be given to it. For example, land required for future occupation should not be acquired until irrigation can be started, and expensive ironwork, etc., should not be purchased much before the time it has to be erected.

When devising a programme for construction it must be remembered that irrigation has usually a slow growth. Time must be allowed for the cultivators, who generally are poor, to get their lands ready, which is an expensive matter, and to acquire the increased capital necessary for irrigation ; also on a large scheme the existing population may be insufficient to develop it, and colonists from outside may have to be attracted, and that also takes time. It is best therefore, if practicable, not to incur expenditure much before it is necessary to meet the irrigation requirements, and, if possible, to construct the works in progressive stages. Thus the sum at charge will be chiefly revenue producing, and will not be causing interest charges to mount up unbalanced by receipts. It should be a financial axiom that when a large scheme can be carried out in such stages, it should not be commenced of full size. The latter procedure will result at first in comparatively small gross revenue when irrigation is being started, and the net revenue will be out of proportion smaller, owing to maintenance charges being increased by the size of the project. As soon, however, as the major works comprised in any stage are constructed, the minor works of distribution in connection with them should at once be completed, so that irrigation may be conducted without hindrance. To delay the execution of the latter, would resemble the establishment of a factory and its driving power without making provision for the machinery necessary to utilise that power.

If a scheme cannot be carried out in stages each complete in itself, which is the best arrangement, much may be done by making the project expansible as a whole, to start it on a comparatively small scale, and to enlarge it so as to keep somewhat in advance of the requirements of increasing irrigation. Thus the canal earthworks might at first be reduced somewhat in depth and section, while the sills of regulators and the beds of cross-drainages would still be constructed at their designed final level and these works of their designed full section; the canal banks might be set back so as to obtain wide berms which would become staunch by silting; and regulators might have blank arches at the flanks. Then when the time came for enlarging the canal to its designed full size, its section could be increased without much alteration, or reconstruction, of its masonry works. Similarly, if there is a fair probability of the necessity arising for subsequently enlarging the canal as originally planned, its masonry works should from the first be constructed to allow of their expansion at the minimum expense.

For irrigation works it would be a great convenience if the financial year corresponded with the seasonal year as affecting agriculture: this would lead to some saving, for often at the close of the former money is wasted in the endeavour to avoid lapse of allotments. In India the monsoon has such a predominant effect on agriculture and on the construction of works, that its close might well be adopted as the beginning of the irrigation year. Works have, anyhow, to be advanced to a safe stage before the monsoon breaks, and during its continuance are more or less at a standstill; it would be both a convenience and an economy if that period were devoted to closing the current year's accounts and preparing a programme for the whole of the ensuing fair weather months. Many trade and other interests are affected by the prevalence of the monsoon and would be benefited if the proposed change were adopted.

CHAPTER IX.

WATER RATES.

ALL water used on land is derived from the rainfall (including dew and snow), and is thus the gift of Nature. It might therefore at first be thought that it should be utilised free of charge, and this is the case with private water falling on, or rising upon, a private estate. In the case of public water which is shared by many, a charge for it is necessary and justifiable for the following reasons. First, in order that it may be used a large amount of expenditure has to be incurred (this the private owner has himself to defray) on the construction of the necessary works, and on their maintenance. Next, the water is derived from the rainfall precipitated on the country generally but can be utilised only by a small number of the whole population : it is therefore fair that they should pay for its use, and thus reduce the taxation of the otherwise not benefited members of the community. Lastly, when water is made available for irrigation, it greatly increases the value of the land to which it is applied, and unless the owners of that paid for their annual supply, they would benefit unduly by unearned increment.

Water rates should provide for the following—interest on the cost of the works, charges for upkeep, and charges for the actual value of the water. Provision for a sinking fund is not necessary for the works should be maintained so as permanently to be in good order. The imposition of water rates gives irrigation a quasi-commercial character, and this should be borne in mind by the engineer in reducing the cost of construction and maintenance as much as possible, and by the administrator in assessing moderately the inherent value of the water as far as that is just to the general taxpayer. Fair water rates will encourage the growth of irrigation ; they will thus directly benefit the cultivators and their labourers, and indirectly the whole population and the State. Unduly high ones will have the opposite effects, and, if excessive, may prevent the agriculturists from irrigating and induce them to depend solely upon rainfall for their cultivation.

The limit to be fixed for the value of the water should bear some relation to the increment in value of the land when facilities for its irrigation are provided at the public expense. The limit for the total charge should be in some proportion to the average profit from the crop, seeing that irrigation is only one item of expenditure and only one factor of the general result, which also depends upon climate, the nature of the soil and other conditions. As profit may be difficult to ascertain and may vary from external causes, a small proportion of the value of the crop is usually taken. Thus the average water rate is in India one-tenth the value of the crop, in Egypt about one-seventh, and in America from one-sixth to one-fifth.

When fixing water rates consideration should still be had to the quasi-commercial aspect of irrigation. Theoretically, they should have reference to the actual amount of water applied or devoted to the fields. They would thus be increased for distant lands (to which the loss in transit is great), for porous, absorbent soils, and areas visited by light rainfall, which conditions entail greater consumption of water. Practically, it has been found (as in the case of the postal and telegraph rates of a country, where the cost of the service also varies according to the distance and nature of manipulation, etc.) preferable to charge uniform water rates throughout an irrigation system or large district. Results may thus be pooled to a certain extent so as better to gain general development. At the start of irrigation the rates should be low, so as to allow for the initial cost of preparing the land, and so as to encourage the cultivators to irrigate. Thereafter they may be gradually increased, say, at intervals of five years, until eventually they produce a proper commercial return, and then should be altered only as changed circumstances demand or justify. They should not be fixed in perpetuity as this will destroy the necessary flexibility in charge which is required in all commercial transactions. Nor should they be imposed by law which will practically have a similar effect, for which reason legislatures do not ordinarily interfere with the law of supply and demand—when they do, the results are usually disastrous. The settlement of rates should be left in the hands of administrators to determine in accordance with the general principles stated above. A commercially justifiable variation in charge is for different classes of crops, as they require such different amounts of water and have such different values. Similarly, for administrative reasons rates may be adjusted to discourage the growth of crops which, although inferior, need excessive supply, or may render the climate insalubrious, or may be advantageously displaced by other kinds.

There are two main methods of assessment of water—by the area and crop to which it is applied, or by the quantity used as ascertained from actual measurement of the supply by modules or in bulk. The latter system has been adopted in advanced countries, and is recommended by its supporters as leading to great economy of water (p. 70). In India the former is almost the invariable practice, as it has been in force for centuries and is well understood by its simple cultivators ; they might dispute the measurement by volume but could not question that by area. The latter system seems best adapted to temperate climates where the conditions of supply are fairly constant : still, even there, where the nature of the soil varies, unless this is taken into account, the charge for water will differ from area to area. In tropical climates the supply available varies enormously between seasons of drought and ones of plentiful rainfall : a uniform charge there would be too low for the value of the water in the first, or too high in the second to induce expansion of irrigation. The economical use of water on the crop system of assessment is best secured by rotation of supply and careful supervision.

In India there are other methods of assessment practised on a comparatively small scale. One of these is the consolidation of rates for land and water where the State owns both, and where average conditions have been ascertained by lengthy experience. The ultimate development of this occurs under small perennial streams on certain village areas, which are subdivided so that on each main part a single crop is grown in rotation with the other parts by all the joint owners simultaneously. This arrangement secures easy administration and small interference with the cultivators, but does not lead to expansion of the irrigated area. A more modern development is the " block system " under which the cultivators group themselves in blocks which are guaranteed, under conditions, a fixed amount of supply in rotation and for a short term of years, and its distribution and extent of application are left in their hands. The balance supply available is utilised for extra land under ordinary crop rates. Thus the advantages of the systems of sale of water by measurement and of consolidated assessment are secured, while the growth of the irrigated area is stimulated by the economy with which the supply is utilised. This system seems best adapted to conditions which exist in India.

CHAPTER X.

EXPERIMENTAL DEVELOPMENT.

IN all scientific professions progress depends much upon experiment, for it should be based on the facts thus ascertained. This is emphatically the case with irrigation, as that has to be studied from hydrographic, constructional and maintenance engineering, and from practical agricultural points of view. With such a complex subject it is advisable to entrust the investigations in respect of each branch to experts, who should, however, work in co-operation with one another in order to secure the best general results. At the same time the ordinary irrigation practitioner should make himself well acquainted with all branches of his work, so that he may apply most successfully the results obtained by the specialists. To enable those specialists to make the most of their opportunities, they should be freed from routine work as much as possible, should be given a reasonably free hand in devising and carrying out their experiments, and should hold their posts as long as possible. The last is a most important consideration, for Nature works in cycles of some duration, and if an observer is subject to frequent transfer, it is impossible for him to gain a thorough knowledge of the phenomena he is studying, and to acquire that local experience which will best fit him to improve his work while still maintaining its continuity. Owing to the general conditions of official service these advantages cannot be obtained by the ordinary practitioner : thus, he cannot devote much time to pure experiment, as he has to attend chiefly to the practical duties of his charge, and therefore should be given the assistance of the specialist to furnish him with the data he requires.

In Chapters IV., V. and XII. matters connected with the nature and scope of hydrographic experiments are described in some detail so that further notice of them is unnecessary here. In regard to constructional engineering it is important that there should be a central testing station to determine particulars as to all materials in common use, and how they are affected by exposure to the weather, long-continued water pressure and the action of deleterious salts, and as to the best measures to be taken, when necessary, to preserve them. It will be of great assistance to the staff generally, and to junior officers particularly, if type designs of works are drawn up and circulated. Such types should not be looked upon as rigidly prescribed and as ones from which no variation is permissible. Rather, they should be regarded as general guides which should be modified to suit local conditions, and the improvement of which will be encouraged. The usual tendency in large official organisations is to favour the observance of routine and to discourage deviations from prescription. The first procedure produces elasticity and evolves originality, which under due regulation secures progress ; the second causes rigidity and stunts the faculty of design, and thus retards development. Every engineer should constantly endeavour to improve on the work of his predecessors, but the young should remember that evolution is better than revolution, and that but few are successful in striking out entirely new departures from established practice. In connection with the type designs should be issued standard specifications (also for general guidance) and model calculations. Still further to encourage investigation engineers in charge of large or novel works should be urged to record their experience in professional papers. Visits by engineers to works in charges other than their own will be productive of instruction, and should lead to the adoption of the most modern successful practice. Senior officers might find it difficult to make such visits, and have, moreover, had diversified experience in their careers. Junior officers can be more readily spared for short times at intervals to examine works outside their own districts, and will thus quickly and early acquire varied practical knowledge which will be of much use to them and of benefit to their charges. Lastly, it will be of great advantage to the seniors to meet in conference, say, annually, to discuss matters of professional interest. In India, with its great distances, large charges and much work, the profession suffers from want of inter-communication, but, if steps similar to those noted above are taken, that want will be met to a considerable extent.

In respect to maintenance engineering, experiments will chiefly be desirable to increase the duty of water, the general principles of which are discussed in Chapter XIX. In addition to determining the duty of complete projects at the source of supply and that close to the irrigated area, more detailed observations are advantageous. The experiments might compare the results on large and small areas ; on soils of different constitution, and on ground of varied slopes; on distinctive classes of crops; and, what is of the greatest importance, on cultivation by agriculturists with different characteristics. Other experiments might be made as to lessening the loss by seepage and percolation ; determining the rise of subsoil water ; the best size and shape of irrigation plots ; the most effective system of rotation of supply ; the various problems connected with the regulation of silting ; and as to other details of maintenance.

Agricultural experiments can best be devised by agricultural experts, but it may be noted here that these might include investigations as to the most profitable crops to grow ; the most suitable programme for cultural operations ; superior methods of cultivation ; the most remunerative manures ; soil and water analyses ; and the number, frequency and depths of waterings required. Cultivators should be instructed how to market their out-turn and in the advantages of co-operation. Further development can be assured by the issue of simple bulletins of instruction, by the tours of itinerating instructors, and by the institution of agricultural shows. Cultivators are everywhere conservative, and perhaps more so in India than elsewhere, but even there have shown remarkable appreciation of such efforts to improve their methods. They require advice which is practical, although it is based on theoretical experiment, and such as can be followed by simple means and without much risk. As in the case of engineers, agricultural experts will benefit by inter-communication with each other.

In conclusion it may be said that all experiments should have practical ends in view, that they should be carried out to conclusion so as to obtain definite and complete data, that they should be recorded clearly and concisely, and that they should have their general results tabulated for easy reference.

CHAPTER XI.

RAINFALL.

RAINFALL, including snowfall and dew, is the source of all water supply for irrigation. It may be utilised directly from that precipitated on the irrigated area, or indirectly from that producing stream flow or subsoil saturation. Stream flow may be led directly into a canal system, by a diversion weir, or pumps, or indirectly into such a system after it has been impounded in a reservoir. Subsoil water is tapped by wells, bores or galleries, and usually has to be raised by pumps or other mechanical appliances. Rain falling on the irrigated area is highly advantageous, as it is supplied without loss or labour, is free from injurious salts, is charged with air, and occasionally with beneficial gases, and usually is at a higher temperature than artificially supplied water. The objections to rainfall are that it is beyond human control and varies greatly, especially in the tropics, in intensity, amount and periodicity. Moreover, being practically pure, it acts only as a solvent of plant food in the soil; it thus exhausts that and therefore necessitates the application of artificial manures to maintain fertility. It is said that 2 inches of rain, falling irregularly, are equal to 1 inch of irrigation water, supplied when required, but the variation of the rainfall makes the comparison difficult. To enable results to be better compared, it is therefore desirable to record if individual showers are useful, or useless, to cultivation, and to take only the former into account. Rainfall should be utilised as much as possible so as to reduce draw-off from storage—crops should therefore be started in the proper season after the ground is then well wetted by rain and before supply from storage is available; light falls should be succeeded at once by light irrigation to drive the natural saturation into the ground and not let it be rapidly evaporated from the surface.

After rain has fallen, part of it is evaporated from the surface of the ground and by vegetation; part of it penetrates into the subsoils and may re-appear, either wholly or partially, in streams as springs or seepage ; and the balance " runs off " the surface and forms flood flow. The greater part of the loss of rainfall is thus due to evaporation ; it will be at its maximum when the rainfall is light and prolonged, and the drainage area flat and absorbent ; and at its minimum when the natural conditions are the reverse. The yield from springs and seepage is largest in the temperate zones where the rainfall is light and frequent, and the ground absorbent. The amount discharged by floods is greatest in the tropics, where the rain falls in violent storms at long intervals, and the ground is either naturally non-absorbent or becomes so by saturation. Stream flow should be utilised as much as practicable; it furnishes the cheapest source of supply for irrigation when it is prolonged and sufficient; when it is long-lived but insufficient it has to be aided by the utilisation of subsoil water, or the storage of storm flow; when it is short-lived, dependence cannot be placed upon it, and irrigation has then to be arranged for entirely from one or another of the other sources of supply.

Rainfall is due primarily to evaporation by the sun from large water areas. Any variation of the total rainfall will thus be due to an alteration of solar radiation, and any general diminution of rainfall is therefore not likely to take place in short historic periods: the distribution of the whole fall may, however, alter. In certain countries a decrease of rainfall has occurred within a comparatively short period ; in others it has taken place over a longer time and to a greater extent, so that once cultivated areas are now deserts. This change must be due to altered local conditions, and one of the principal of these is believed to be deforestation. Although the total rainfall of the whole world remains practically constant, it varies from year to year at the same place, and also from place to place during the same year : this variation is one of the characteristics of rainfall and cannot be predicted. Despite this variation, when long periods are taken into account, the mean rainfall at most places observed does not alter much. Meteorologists believe the fall takes places in cycles of about thirty-five years, and that the average annual fall of such cycles does not vary by more than 2 per cent. The time during which systematic observations have been made is, however, comparatively short, and this opinion may have to be modified when the record becomes longer. Taking the mean British rainfall for a long series of years as 1.00, the rainfall for abnormal years is—the wettest year, about 1.50 ; the driest, 0.67 ; the average of the driest two consecutive years, 0.75 ; and the average of the driest three consecutive years, 0.80. In the tropics the variation of the fall of abnormal years is still greater, and, although it is believed statistics have not similarly been worked out, may perhaps be said to be from 0.25 to 2.00 : the first results in scarcity, and the second in great damage by floods. The general variation of rainfall does not depend entirely on latitude, but also on local conditions, such as the altitude of the land, the distance from the sea, the nearness to mountainous areas, and the character and direction of the prevailing winds. The popular idea that rain can be compelled to fall by causing explosions is not tenable. First of all, rain cannot be obtained when the air is not saturated with moisture ; next, precipitation depends upon condensation, whereas an explosion, by disturbing the air particles, produces friction, and that generates heat. A smoky atmosphere, by affording nuclei on which the air moisture can condense, may have some effect in this respect.

In regard to altitude rainfall generally increases with the height, which is accompanied by rarefaction of the air, and that diminishes the amount of moisture which can be held in suspension. Generally for the sake of accessibility raingauges are established on low ground, and but few are placed on high ground, and this may lead to an underestimation of the average rainfall. The proper way is to regulate the number of the former in due proportion to that of the latter. Where inaccessibility introduces difficulty, that may be met by using automatic raingauges which need not be visited frequently, as they can register the fall for a fortnight. Such instruments have the further advantage that they record, not only the amounts, but also the time and the intensity of the different falls.

The distance from the sea affects the variation of the fall, for if the air near the coast precipitates much rain, its current thus dried may pass over the country beyond without producing heavy precipitation: thereafter, the air may either concentrate its moisture, or receive additions to it, and this may result in increased rainfall.

In respect to mountainous areas it is generally on the sheltered, or leeward, side that the heaviest downpours occur, and not on the exposed, or windward side. This may be due to the cooling of the moisture-laden current by the latter, and to the precipitation being carried onward to the former by the wind. A notable instance of this happens along the Western Ghats, Bombay Presidency; there the rainfall increases from the seaboard until the crest of this mountain range is reached, immediately beyond which it attains its maximum. Two to five miles from the crest eastwards the rainfall decreases by one-half, and thirty miles further on, to one-quarter of the fall at the watershed itself: thereafter, is a "dry zone" characterised by a low rainfall, and beyond that there is increased precipitation.

The character of the prevailing winds greatly affects the amount of rainfall. If the wind on its passage passes over a large and heated body of water to the land, such as in the case of the Gulf Stream and Ireland, and in that of the Indian Ocean and India, it will become highly saturated and will thereafter readily part with its excess moisture. If a saturated defined air current travels up a valley, it will precipitate more rain on it than if it only traverses it.

Although rain falling outside the cultivated area is the sole source of irrigation water, its total amount is not utilisable, but only a fraction of it which is known as its "yield" and that depends upon other natural conditions which are discussed subsequently (p. 50). It cannot, therefore, be too clearly stated that rainfall statistics do not by themselves furnish sufficient data for calculating the probable amount of supply. Their advantage is that they are much more numerous than discharge statistics, and therefore can be utilised in supplementing the latter. By taking them into account intelligently, some idea can be obtained of what supply may be expected, especially if in the neighbourhood there exists a catchment with similar characteristics for which both rainfall and discharge statistics have been collected for some years, so that the yield of the area under investigation may be deduced from that previously under observation. In the tropics only the heavy falls produce replenishment and there these should alone be considered and the yield of each calculated separately—that is to say, for this purpose the total monsoon rainfall, and still less the total annual fall, should not thus be dealt with. In the temperate zones, where the rainfall is less intense and occurs throughout the year, and supply is greatly dependent upon seepage, which tends to equalise small variations in precipitation, the annual fall is, however, made the basis of calculation of yield. A common mistake committed in dealing with rainfall returns is to take the average rainfall on an area to be the arithmetical mean of the falls registered by the different gauges established on it. Each such gauge represents a certain area on which the amount of rainfall is practically what it itself measures, and the extent of such represented areas should first be ascertained. The true average rainfall on the whole catchment will then be found by multiplying each gauged fall by its represented area, and dividing the sum thus arrived at by the total area of the catchment.

A raingauge should be placed on level ground and there should not be within 90 feet any obstruction of the rain coming to it, such as made by trees, buildings, etc., nor should there be any large abrupt changes of the ground surface within a quarter of a mile of a gauge registering the fall on plain country. Any enclosure round the gauge to protect it from trespassers should similarly not form a solid barrier to rain currents. The rim of the gauge should be fixed level and must be preserved intact so as correctly to measure the fall. The level at which it is fixed is a matter of importance, as the amount of gauged rain is said to decrease 1 per cent. for every additional foot of elevation up to 9 feet above the ground. This has been considered to be due to the greater velocity of the wind at the higher elevation carrying raindrops past the gauge: also, to the parabolic path of raindrops which is normal to the gauge only if its rim is placed near the ground. Another reason may be that the lower strata of the air are saturated by the splashing of the rain on the ground (which splashing is evidenced by mud splatters on walls, etc.), and the raindrops passing through them increase in size, and when caught in the gauge, magnify the actual rainfall. The rim of the gauge is usually placed 1 foot above the ground, but from the above 4 feet would appear to be a more correct elevation, and it would also obviate interference with rain currents by the gauge enclosure. Automatic rain gauges, in addition to the advantages enumerated above under "altitude," are also useful as a check on ordinary gauge observations. Their disadvantages are their expense and the liability of the clockwork to stop, or the pen to become dry and thus not mark the diagram.

CHAPTER XII.

HIGH-FLOOD DISCHARGE FORMULÆ.

EVERY engineer who has long had to deal with rivers in India must be impressed with the variation of their high-flood discharge and the immense volumes of water which rush down their channels when their floods are at their highest. There is no telling when these excessive flows will take place, but it is certain that at some time or another they will occur. Naturally, when designing works full provision must be made to pass them away safely, for, otherwise, during their continuance, it is not possible to control them and extensive damage may result. A washaway on a railway may disorganise the traffic over a great length of line ; the destruction of a road bridge may cause much local inconvenience ; the breaching of a canal may lead to the failure of a large area of crops ; while the bursting of a reservoir, in addition, may result in the loss of life and property for many miles along the course of the stream below it. The proper determination of the probably largest flood is thus a matter of great importance ; if insufficient allowance was made, one or other of the disasters just mentioned may follow ; if superabundant provision was designed, much expenditure will needlessly have been incurred. The importance of the subject has therefore attracted the attention of many investigators, numerous floods have been observed and calculated[1] and several formulæ have been devised in order to predict what may happen.

In spite of all this record it may be doubted if really safe rules exist for determining the sufficient but not excessive provision for high-flood discharging capacity which should be allowed for in a design. This is due to the extremely variable conditions which are the factors of the production of extreme floods. The intensity, duration, extent and direction (in respect to the drainage lines) of the rainfall vary over large areas to such a degree that they

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[1] For an excellent summary of the principal formulæ devised, and for statistics of numerous high floods in several countries, reference may be made to Buckley's Irrigation Pocket Book, 3rd edition, pp. 299-323, E. & F. N. Spon.

cannot be represented by mathematical symbols. Catchments differ greatly from each other in shape and direction and this makes difficult comparison of results from them ; nay, more, in any catchment of considerable size there are many changes of surface slopes, porosity, covering and other physical differences, all of which act in modifying the rate of run-off. In fact, the only unchangeable factor is the extent of the gathering ground (although the effect of this will be altered by the amount of its saturation by rainfall), and this appears to be the reason why it is the only constant in certain well-known high-flood discharge formulæ. The formulæ have, however, the utility that they allow a general idea to be formed of the provision which should be made for the discharge of high floods.

This being the condition of affairs, one hesitates to place full reliance on such formulæ, and the hesitation is not much diminished because some of them are in somewhat elaborate mathematical detail, as this cannot be exactly applied to the whole drainage area with its numerous varying conditions. There is really only one safe guide and that is Dame Nature ; she takes all discharge factors accurately into account and gives the actual flood as the solution of the problem. By observing, calculating and tabulating the discharges of the stream we get reliable data. The objections to this procedure are that it involves many years of study, and during them one can never be sure that all the flood-producing factors were at their maximum effect. The period of investigation can, however, be shortened if a practically similar catchment in the neighbourhood has been under prolonged flood observation and the relative discharges of the two can be compared for a few years. Failing this the best precaution to take is to apply a factor of safety to the observed results and to increase this in inverse proportion to the length of the period of observation.

To return to flood-discharge formulæ. The principal objections to treating the catchment area as a uniform unit have been noticed above. They are met in the formulæ by the introduction of a co-efficient and that is a device which is common to many hydraulic equations. In formulæ connected with the discharge of channels, weirs, etc., the observations on which they are based have been numerous, and the conditions are the same everywhere, so that the variation of the co-efficient is not usually great, and any mistake made in its selection is more likely to result in a comparatively small amount of error than to be attended by great danger. For high-flood formulæ the reverse is frequently the case : the large variation of the co-efficient really reduces the application of the formulæ to guess work, modified by the extent of the selector's experience, and unless that is considerable, may result in a catastrophe or an excessive expenditure. The observations in any single instance depended upon are comparatively few, the physical conditions vary from catchment to catchment, and wrong assumptions may entail much loss.

If all that has been written above is accepted as worthy of consideration, it may well be asked what should be done to get reliable data. The recommendation made is that each large catchment with varying physical conditions in different parts of its area should not be treated as a single unit (see p. 11) but should be divided into constituent portions in each of which the conditions are fairly constant throughout its extent. If careful and prolonged discharge observations are made for such minor areas of typical catchments selected for experiment, eventually a large amount of reliable data will be obtained and can be applied to schemes under investigation, which also would have their gathering grounds divided into units each having fairly uniform conditions. The experiments, like those on which other formulæ are based, will have to be numerous, and still more numerous if varying conditions of rainfall, surface slopes, porosity and covering of the soil are taken into account as they should be. Eventually it may be possible to determine with fair accuracy what co-efficients should be applied to each physical condition, and thereafter these can be utilised to calculate the probable high-flood discharge which should be allowed for in a project.

It may be admitted at once that this large amount of investigation is more than can be devoted to any individual scheme and it is not intended to suggest that it is desirable for a single project. The recommendation made is that the investigations of the discharging capacity of selected areas should be entrusted to a specialist, so that he may work out results which can thereafter be generally applied to particular schemes which are being designed. This is a work which is eminently suited to a hydrographic survey, the establishment of which was recommended in Chapter V. If such surveys are conducted in the different Provinces and large States of India, a very considerable body of reliable data will be collected.

CHAPTER XIII.

HIGH-FLOOD DISCHARGING CAPACITY.

In the last chapter high-flood discharge was discussed in respect of the formulæ in general use to determine it, and investigations were suggested for ascertaining the co-efficient more exactly: also the importance of placing most reliance on actual observations of discharge was urged. Correct observations, or calculations, of discharge are necessary in order, on the one hand, to avoid running a risk by underestimating its amount, and on the other, to prevent undue expenditure being incurred on making excess provision for its disposal. Cross-drainage works must have a flood discharging capacity equal at least to the extent of the greatest flood anticipated. Reservoirs with ordinary level waste weirs, although they at first absorb part of the flood as their surface is being raised thereby, will require an equal discharging capacity when they have attained high-flood level. Reservoirs furnished with large deep-seated sluices and temporary weir crests in order to take advantage of flood-absorption (p. 91) may be designed accordingly to pass out of them floods at a considerably lower rate than that at which these enter them. Very large rivers which beside their central troughs have marginal high flood channels, or low areas, when their surface rises and submerges these, thus absorb parts of floods, and therefore act then like reservoirs of the latter description. Often the amount of gauging required to obtain sufficient knowledge of the behaviour of the catchment cannot be carried out for want of time, and the observations made have to be supplemented by calculations deduced from the behaviour of neighbouring catchments under similar physical conditions. The conditions may not, however, be precisely similar, and therefore there should be some general idea of how variations of the different factors causing high-flood discharge affect the result.

The factors producing yield from a catchment are discussed in the next chapter; those affecting high-flood discharge are the same, but some have more pronounced effects than others. In particular, the general conformation of the catchment area has a great influence on the maximum rate of discharge. A catchment with a boundary resembling a semi-circle struck from the site of the work, will tend to have large floods, as the flow of the different tributaries will arrive at that site simultaneously, if their bed slopes, etc., are similar. On the other hand, a long, narrow catchment may have more prolonged and gentler floods, as the maximum flow of the most distant tributaries may arrive at the site after that of the nearest streams has decreased. A defined storm travelling downstream will tend to equalise matters in this respect, and thus to produce a larger flood than one crossing the area, and still larger than one going upstream.

Other important physical conditions which tend to increase flood discharge are impervious, barren and steep slopes and high saturation of the catchment ; also tributaries with steep longitudinal slopes entering main streams with gentle ones. High saturation of the ground increases the discharge capacity of all classes of soil, as temporarily it diminishes their permeability, and when it is prolonged, most of the rainfall will run off, as but little of it will be absorbed. Again in tidal rivers the state of the tide, whether high or low, will greatly affect the levels to which the rivers will rise in the lengths influenced thereby ; high tides will dam them up, while low ones will let them drain away unobstructed.

The principal physical conditions which tend to reduce high-flood discharge are afforested, grass-clad and cultivated areas, and flat slopes of the country, especially when they are dry and absorbent. Swamps and minor reservoirs will also decrease the intensity of flood discharge in the proportions which they bear to their own individual catchments ; if this proportion is so large that they are not completely filled by the run-off into them, they will continue to be efficient flood regulators ; if, however, their capacity is small, they will soon be filled, and thereafter will have but little restraining influence.

In comparing a catchment on which few actual flood observations have been made (see p. 11) with one for which there is a long record thereof, it will be best to analyse them into constituent areas under similar conditions, and from actual experience, or observation, to allot co-efficients of discharge to each of these minor areas, so as thus to arrive at their total relative discharging capacity. In order that a work may be designed safely, the most favourable conditions for producing a maximum flood must be taken into account and provided against, by giving it sufficient flood-discharging capacity so as to render the possibility of its failure remote, for if that occurs, it may cause serious loss to life, property and revenue.

Reliable records of floods are of the utmost importance as guides to the provision necessary for flood discharge. The rise of large floods varies in every year and still more from year to year : the works must be designed to pass the maximum discharge safely, although that may not happen for many years. It is certain, however, that a very high flood will come eventually, and this fact shows the necessity for a long record. It is not certain that the highest flood observed was the maximum possible, *i.e.*, was the result of all the factors of discharge acting simultaneously with their greatest effect. Therefore, when the record extends for twenty-five years or more, to the maximum flood entered therein, a percentage of, say, 10, should be added for safety : as the term of the record diminishes, the percentage should be increased, unless during that period a very high flood occurred. When the record is prepared, it should be noted on it if the flood discharging capacity of the catchment has since been artificially altered, and the probable effect of the change of conditions should be taken into account. Thus, if the country has recently been extensively afforested or tilled, it is likely to produce smaller floods than heretofore : if it has been largely deforested, or drained, larger floods may be expected. All high-flood levels should be permanently marked on the works concerned so as to record them prominently.

Observations will have to be relied upon where there are no records available. The highest known flood will have impressed the local inhabitants, and they may be asked to point out at intervals on a long regular reach of the stream how high it reached on both banks. The points indicated should be examined as to their probable correctness, and as accepted after enquiry, should be marked and levelled, the discharge calculated from the flood longitudinal and cross-sections, and a percentage excess allowed as a provision for safety. In a year of great rainfall and heavy floods as many such observations as possible should be made when the actual high-flood marks will be visible, as such a record will be of much use generally.

The rate of discharge from small catchments is higher than it is for large ones because intense rainfall is not precipitated simultaneously over large areas, nor does its run-off from all parts of their catchments reach the outfalls at the same time. The variation of rate is greatest between small catchments differing from each other in extent, than it is between large ones, similarly unlike in size, because less intense, but still heavy, rain may fall nearly uniformly over large areas at the same time. To illustrate this, the maximum run-off per hour on catchments similar to each other except in regard to area might be taken thus—up to one square mile, 3 inches; for five square miles, 2 inches; for ten square miles, 1½ inches; for twenty square miles, 1 inch; and for two hundred square miles, ½-inch.

Large floods do not consist solely of distilled water, as they may carry down with them heavy silt, stones, boulders, bushes and trees, all of which may lessen the discharging power of the works designed to pass them if provision has not been made therein to deal with these obstructions to flow. In regard to storage reservoirs, waste weirs will not be interfered with by silt, and if there are no crest works, will pass drift timber: if the water surface is kept low in the monsoon to obtain flood-absorption capacity, the undersluices should be protected from being jammed by such timber by means of gratings. Cross-drainage works should be rendered safe from blocking by being built with sufficiently high and wide spans. The undersluices of alluvial weirs also require wide spans for this reason, and will be improved if the alternate piers are given an extra projection upstream to direct water-borne logs and trees through the vents.

In addition to normal high floods, occasionally there are excessive abnormal ones, such as those produced by a cyclone or the bursting of a reservoir. To make permanently adequate provision for these might entail very largely increased expenditure beyond what is sufficient to discharge the run-off from ordinary rainfall: to omit special arrangements for dealing with them might lead to disaster. The most suitable plan is therefore to design extra flood escapes, which, as they will be rarely called into action, can be made and repaired cheaply. For storage reservoirs breaching sections can be constructed at the low flanks of the dams, and safety flood cuts at the ends of the waste weirs. For cross-drainage works additional flood openings might be built at their flanks, and breaching sections formed where the canals pass in low embankment hard ground in their neighbourhood. For alluvial weirs more undersluices might be constructed.

CHAPTER XIV.

YIELD OF CATCHMENTS AND RIVER DISCHARGE.

WHEN dealing with rainfall in Chapter XI., it was noted on p. 41 that, although this is the sole source of supply of water for irrigation, its whole amount cannot be made available for that purpose, because, on account of other natural conditions only a portion of it is thus utilisable. That portion is known as the "yield" of the catchment concerned, which is the total amount of water discharged by the stream draining the area, inclusive of storm floods and ordinary flow and seepage. The balance of the rainfall is lost by evaporation and by deep-seated absorption which does not return water to the surface as seepage. The yield of a catchment depends upon various factors of discharge, the first of which is its size. Next, come conditions of the surface—whether that is hilly, sloping or flat; barren, grass clad or cultivated; treeless or wooded; impermeable or permeable; wet or dry; free from or containing minor reservoirs or swamps. Lastly, there are the meteorological conditions connected with the extent, intensity and frequency of the heavy falls of rain (which in the tropics produce practically all the run-off); and the position of the catchment with reference to such falls. Although the yield depends primarily upon the rainfall, its amount varies with the factors just noted. The surface ones mentioned first in each clause tend to produce violent, short-lived discharges, which are those most useful for reservoir replenishment; the others, detailed afterwards, gentler and more prolonged flow, which chiefly benefits works deriving their supplies direct from rivers. In the tropics the yield is almost entirely due to heavy rain falling at comparatively long intervals and running off quickly, and this fact renders storage necessary there on all but large or absorptive drainage areas. In the temperate zones most of the yield is due to seepage, which enters the rivers for many days after rain has fallen. It is thus easier to calculate, or estimate, the yield of individual falls of rain in the former than it is in the latter: on the other hand, it is more difficult to gauge storm discharges than to measure gentle long-lived flows.

To determine the sufficiency of a catchment for a proposed storage work from its rainfall record alone, it is necessary to assume coefficients, so as to reduce the amount of the gauged fall to what will be its probable yield. In the tropics these coefficients should vary with each fall, so that their selection requires the exercise of knowledge gained by general experience, or better, from that derived from the results attained on a neighbouring work constructed under similar conditions. It would be erroneous to take into account the whole monsoon fall and apply a single coefficient to it, and still more mistaken to deal thus with the total annual fall. To save trouble, but at the expense of accuracy, all the falls of heavy rain, each of which will produce run-off, might be lumped together and a single coefficient adopted for the sum. In the temperate zones the estimation of yield might be made by taking into consideration each month's fall separately, and similarly applying the coefficient properly relative to it—here again experience, as noted above, is essential as a reliable guide. Having calculated the yield, the consumption should be estimated, and this should include utilised draw-off and waste due to evaporation and absorption. The figures thus obtained might be entered in a tabular form, month by month, and the difference between the yield and consumption will thus represent the amount of storage practicable; or, better, the results might be plotted to form a storage diagram.[1] The full-supply capacity of the reservoir has first to be assumed, for, when it is attained, further immediate yield will run to waste and be lost. If the table or diagram shows that at the end of the year there is a *minus* storage, the assumed reservoir capacity should be increased, if flood water has run to waste and can be utilised, but if there has been no wastage, the extent of draw-off for irrigation should be diminished. If, however, a *plus* storage is then indicated, the irrigable area under command should be increased to take advantage of the surplus. To determine the amount of storage desirable, it would be necessary to consider the diagrams of several normal years, and to exclude years of abnormally heavy or light rainfall.

It is practically impossible to arrive at the sufficiency of natural river discharge, to be utilised directly from a pick-up weir, merely

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[1] See Minutes of Proceedings, Inst. C. E., Vol. lxxi, pp. 270-278.—"The Capacity of Storage Reservoirs for Water Supply," by W. Rippl.

from consideration of the rainfall record of its catchment, as the controlling factor in this case is the amount of seepage producing long lived utilisable flow, and that can be determined only by experimental gauging. Here again estimation of the probable amount and duration of the flow of the stream under examination can be aided by comparison with actual previous observation of a neighbouring stream under similar natural conditions. It may be assumed that the discharges of the two will be in proportion to the extent of their drainage areas, or will vary generally according to their differences of flow as established by comparative gaugings during a few years.

There is also the case where natural river discharge has similarly to be utilised, but is known to be insufficient, and has therefore to be supplemented from storage, the amount of which has to be estimated. This is a combination of the two previous cases and has to be treated accordingly, so as to determine what is the minimum amount of storage required in order to take the fullest advantage of the natural fair weather flow available. It will be best to tabulate results, month by month. First, the quantity required to supply the canal should be estimated, and next, the amount of discharge of the natural stream should be gauged at the site of the weir proposed for it ; these should be shown in separate columns. The differences between these figures should be entered in two other columns, the first having entries of amounts required from storage, and the second, those available for storage, excluding floods which will have to be run to waste. The full-supply storage of the reservoir should first be assumed as before, and also its initial storage before draw-off takes place, and then its contents month by month can be calculated and tabulated from the two previous columns. The actual full-supply storage required can be arrived at as in the case first discussed. Should the feeding reservoir be formed at a site considerably upstream of the canal weir, the consequent effect of the reduction of the catchment area should be taken into account.

The general conditions governing the yield of catchments and river discharge were stated at the beginning of this chapter, and thereafter methods for estimating them have been discussed. It now remains to point out that estimates cannot safely be accepted (see p. 130) having regard to the varying hydrographic conditions which govern stream flow, and that, at the best, they can furnish only approximations. Errors in assumptions may lead

CHAPTER XV.

SEEPAGE.

SEEPAGE may be defined as water which by the action of capillary attraction passes underground from the source of supply, through close soils by general diffusion, and does not appear visibly in the neighbourhood. If it reappears it will generally emerge along the margins of streams and their tributaries and increase their discharge, but it may lead to the swamping of low-lying land. Some of it may continue its subterranean course until it reaches the sea and can then be utilised on the surface only by tapping it by means of wells, which usually will be deep. In contradistinction to seepage, percolation (Chapter XVI.), may be described as water which by the action of gravitation passes under or above ground from the source of supply in defined channels, through more or less open soils, or fissures, and appears visibly in neighbouring wells or drainage channels. Being less deep-seated and more concentrated than seepage, it is generally easier to utilise it.

It is seepage which produces most of the fair-weather flow of streams. In countries with deep porous soil and having temperate climates and gentle rainfall distributed throughout the year, most of the discharge of streams is due to seepage and is thus more uniform and prolonged. In parts of the tropics, where the soil is shallow, the surface steep and the bulk of the rainfall occurs in violent storms in one season, short-lived floods are frequent, seepage is small and the fair-weather flow rapidly diminishes. Seepage there may be classed as " natural " (depending upon the rainfall on dry areas) or " artificial " (due to irrigation). The former is likely to remain constant so far as the subsoils are concerned, as their porosity is settled by long-established conditions, and to vary directly as the saturation due to the amount, intensity and periodicity of the rainfall. The latter will at first probably decrease slowly as the newly moistened subsoils get their pores choked by infiltering matters and become more consolidated by the increased superincumbent weight: such decrease may, however, be made good by the effect of an increase in the irrigated area. Eventually, when the conditions have become stabilised, artificial seepage will resemble natural seepage in regard to the variation of its amount by the character of the surface saturation.

It is to seepage that the " loss by absorption " on irrigation works is practically due. On canals in alluvial soils in Upper India about six-sevenths of the total loss in transit is reckoned as caused by seepage, and the balance by evaporation from the surface of the water. These are average proportions, for variations in the former are due to subsoil conditions, and in the latter to climatic ones. The Bari Doab Canal experiments give the total loss in the canals and distributaries as 26 per cent. of the head supply, and 21 per cent. of that in the watercourses : thus its amount is very considerable. On reservoirs it is difficult to separate the two losses, but it may be said that absorption tends to diminish as the beds get waterproofed by silt, while evaporation remains steady under the same climatic conditions. For the combined loss the usual allowance made in Bombay is four feet vertical on the mean area of the reservoir surface : evaporation generally accounts for the bulk of this.

This large amount of loss greatly reduces the irrigating capacity of the works, thus increasing their capital loss per acre irrigated and diminishing the financial return from them and the benefit to the irrigating community, and hence to the country generally. Other disadvantages are due to it on the irrigated area itself : the water in escaping underground carries with it a portion of the fertilising matters applied to the soil and thus increases the cost of cultivation, or diminishes the out-turn of the crops. A greater one occurs in retentive soils charged with alkaline salts which may thereby be brought to the surface by capillary attraction and so render the land more or less sterile. Excessive seepage from upper lands, beyond what the subsoil can pass away underground, will waterlog the lower lands, and will sour the soil by preventing its aeration, and will thus reduce or stop the growth of crops. Moreover, the safety of earthen dams and high embankments may be endangered if the subsoil is by seepage rendered too soft to support them.

The necessity for reducing seepage as much as is practicable is thus evident. In the first place careful selection of the sites of the works and of the area to be irrigated should be made with this object in view. Reservoirs should not be constructed where their basins expose fissured strata, or highly porous soils, unless muddy inflow is likely to staunch them rapidly, but such inflow will have the disadvantage of reducing the capacity by excessive silting. The sites of dams should be as water-tight as possible.

Dams should be founded on dense unfissured water-tight strata, and earthen ones should have substantial puddle trenches similarly founded. If a large amount of seepage is still anticipated it should be intercepted by deep seated drains to lead it to the streams and prevent it from waterlogging the country below.

Canals should not be led through porous formations nor close to depressions, which may induce excessive subsoil flow, nor should they traverse alkaline soils. Careful observations of the loss in transit in different sections of them should be made, and defective ones should be rendered staunch either by puddle trenches, linings, or waterproofing by admitted earth or silt. The irrigated area should not be underlain by porous formations reaching nearly to the surface. The rise of the subsoil water should be under constant observation, and if it occurs unduly, should be prevented either by reducing the amount of supply given to the fields or the area of irrigation; the construction of wells to lower the water-table should be encouraged, and finally, if necessary, drainage channels should be excavated to carry off the excess saturation.

Seepage, has, however, an advantage as well as disadvantages, and that is it renders possible the utilisation of water more than once. The fair-weather discharge of the lower Indus in Sind depends much upon the seepage from the upper Punjab irrigation and increases with it. That irrigation is carried on chiefly in the monsoon when the supply in the river is superabundant, and its extension will thus, by slow sub-soil flow benefit the lower country at a time when surface water is in deficit. A series of pick-up weirs on a stream is peculiarly adapted to increasing in this way the amount of the natural discharge, and chains of reservoirs one below the other similarly receive additional replenishment.

Not only must the amount of seepage be considered but also the time when it reaches the stream: what arrives during the monsoon is of small use except for augmenting storage, but what enters it during the fair-weather is of great advantage to all classes of irrigation works as it gives them additional supply when that is most required. The character of the seepage water must also be taken into account and should be ascertained by analysis : that coming from manured lands should have fertilising properties, while that from alkaline areas will probably be detrimental. The rate of travel, the amount of seepage, and the quality of the water should therefore be determined by careful experiments before works are designed to utilise the supply thus made available for irrigation.

CHAPTER XVI.

PERCOLATION AND WORKS.

PERCOLATION may be defined to be water which by the action of gravitation, or pressure, passes under or above ground from the source of supply, through more or less open soils or fissures, and appears visibly in the vicinity, or in neighbouring wells, or drainage channels. Another name given to it is "leakage." Percolation at irrigation works of course causes loss of supply which is undesirable, but its steady amount when these are constructed with ordinary care is not great, and may in some cases be submitted to if its practically entire suppression would entail much expense. When, however, danger is likely to ensue from it, its excessive amount must be prevented at all costs. What has to be guarded against is a large increase of percolation, whereby defined channels will be produced, under or through a structure, and will enlarge so as to form passages in which an uncontrollable discharge will take place and lead to the destruction of the work. The principles to be followed in dealing with percolation therefore are, first, to take every precaution in design and construction to cut it off; and, second, if these are not entirely successful, to provide means of drainage whereby the excess subsoil flow can be passed safely out of the work and its increase can be prevented. When a structure is founded on otherwise sound but leaky strata, a third principle is to treat it as entirely submerged and thus buoyed up by the subsoil flow, and to design its mass accordingly. With these preliminary remarks the way in which effect is given to these principles in certain types of work will shortly be described.

Masonry dams should have their foundations made staunch as described on p. 106. In spite of precautions, percolation may not be entirely cut off at the base, and may take place from water finding its way under great pressure through the body of the dam or at the flanks: such internal flow should be intercepted and passed out of the work by a system of drains. In the Vyrnwy Dam this was arranged for by constructing a longitudinal drain, or tunnel, about the centre line of the dam with its sill above the downstream backwater level, and discharging out of the dam through a cross tunnel. Along each of the more important foundation valley beds (not, however, within fifteen feet from the faces of the dam) a minor longitudinal drain was led and connected by a vertical branch with the main tunnel. The amount of drainage has always been small and fluctuates very slightly. Cracks may be produced in the masonry by unequal settlement at places where the foundation level changes abruptly ; they will be avoided if the lower part of the construction is first carried up to the higher level and allowed sufficient time to set and consolidate before the superstructure is raised further. Other cracks may be caused by variation of temperature which leads to great stress on the masonry if that is constructed with rigid cement, especially near the thin top of the dam, and they may admit water, but these cracks should not go deep into the cross section as the hearting does not vary much in temperature. To prevent this damage it has been proposed to bury iron rods in the top of the dam ; if cracking is avoided there it is not likely to start lower down. If instead of rigid cement the masonry is built with elastic hydraulic lime, this cracking is not probable, as the slow setting of the latter allows initial strains to adjust themselves. A dam curved in plan by its elasticity resists the effects of temperature changes better than does a straight one. Lastly, water under great pressure in the reservoir may penetrate into the dam : if the amount is small, it will probably decrease rapidly as the masonry compresses itself and the mortar expands during setting, thus reducing its pores ; if, however, the amount is large, it can be lessened by pointing or setting the face stones in cement or gauged mortar, or by plastering similarly the whole face if the stones themselves are porous.

Earthen dams in respect to their foundations should be treated as described on p. 107. Theoretically, below a dam resting on homogeneous soil and having equal side slopes, the lines of percolation flow are a series of confocal ellipses owing to the increased resistance produced by the central puddle trench, and the greater weight of the dam at its centre than at its toes, compressing the soil in correspondingly varying amount. Practically the course of that flow will depend upon the variation of the porosity of the subsoil and the presence, or absence, of permeable planes at different depths. Assuming the existence of the confocal ellipses, it will be seen that a downstream drain is cheapest if formed near and outside the toe than under the dam, is equally effective in intercepting and passing off percolation, and is superior in that it can subsequently be attended to if necessary. Similarly, the puddle trench might be placed near the upstream toe, but if this were done it might be passed over by percolation through the dam, and it would cause unequal settlement of the earthwork on each side of it which would tend to produce leaks. For these reasons the trench is almost invariably formed at the centre line of the dam, although there its cost is at a maximum. Percolation in excess through an earthen dam is what has chiefly to be guarded against as it may sodden the earthwork or its foundations, and cause extensive settlements or subsidences, and if it is concentrated along definite leakage planes, may lead to slips. Every precaution should therefore be taken to resist it and to drain off harmlessly any which is not otherwise intercepted. Percolation through the dam will occur on the upstream side from the reservoir or into it on the downstream side from the rainfall, according to the nature of its earthwork, and in the former case, in proportion to the water pressure, and the flow will take place in a curved vertical plane. It should be the object of the constructor to make this curved plane as steep as possible at its upstream end and to end it as near ground level as may be at the centre line of the dam. This can be accomplished by forming the earthwork upstream of good watertight material and consolidating it thoroughly. The earthwork downstream of the centre line, to allow of self-drainage, should be of porous material also consolidated, and should be underlaid by subsoil drains. Throughout, the construction should be homogeneous so as to avoid the formation of leakage planes, and should be carried up slowly and uniformly to prevent that of settlement planes and fissures. As much time as practicable should be given for the dam to consolidate itself by settlement before it is subjected to water pressure from the reservoir: for this reason the highest parts should be commenced first.

Masonry weirs may receive the same treatment as masonry dams, but ordinarily should not require further precautions than founding and constructing them securely. Their height being usually much less than that of dams, the water pressure will correspondingly be small at first, and will probably be reduced eventually by the silting of the backwater. If, however, the height of the weir is considerable and the depth of discharge over the crest great, the concussion of the overfall may shake the foundations, or undermine the structure, and tend to cause leaks. In such a case the base of the work should be carried well into sound rock and be protected by a water cushion downstream. Weirs on fissured rock, which although not watertight is otherwise sound, should be treated as wholly submerged, so that the weight of their masonry is virtually reduced by that of the water they displace, and their section should be calculated accordingly.

Alluvial weirs are usually founded on sand, a highly permeable material, which, however, offers some resistance to subsoil flow, and has the advantage that defined leakage planes are seldom met with, although they may be induced to form by wrong treatment. Percolation passes under such a weir with a hydraulic gradient on the steepness of which depends the amount and velocity of subsoil flow. The finer the sand, the less will be the interstitial spaces in it, and the slower the flow through it, but the less also will be its resistance to being transported by the subsoil current. By forming the weir with a long base, the slope of the hydraulic gradient (from the inlet upstream to the exit downstream) *can be adjusted artificially to the nature of the sand, so as to* reduce the subsoil flow to a very small amount, and to lessen its exit flow to so low a velocity that it will be unable to carry away the grains. Part of the length of the base is placed upstream of the crest wall of the weir to form the " upstream apron," which lowers the hydraulic gradient, and diminishes the pressure on the structure downstream of it (p. 83). This upstream apron is not subjected to erosion or overfall and can thus be formed of cheap materials (usually concrete blocks resting on puddle) but it must be elastic and watertight and be in perfectly staunch connection with the crest wall. Further to increase its efficiency, it is usually finished off upstream by a longitudinal line of sheet piling. The crest wall should be founded deep—to increase its stability; to lower the hydraulic gradient downstream, by virtually adding to its length twice the depth of the foundations ; and to reduce the volume of sand through which free flow takes place. The balance of the base of the weir consists of the " downstream apron," which is formed with a gentle slope to lessen the velocity and hence the erosive action of the water passing over it. It forms a cover to the sand underlying it, thus continuing the hydraulic gradient to its toe, where the water has a free exit which prevents it from heading up upstream and intensifying the upward pressures on the whole work.

The pressure of the water in the sand under a weir acts in two main directions, horizontally and vertically. The horizontal action tends to undermine the weir and is known as " piping " : it is prevented by making the total foundation of the work, and especially the upstream apron, of ample length ; securing both the upstream and downstream toes from scour by parallel currents (projecting divide walls are designed to induce regular flow over the crest) ; and by cutting off lines of subsoil flow by curtain walls at the toes and by core walls projecting below the face of the downstream apron. The silting up of the backwater, natural or artificial (by throwing earth on to the river bed), and the staunching of the body of the weir by silt carried into it, will also reduce piping. The vertical action of water pressure is known as "fountaining," and may be due to—insufficient thickness of the weir ; defective construction whereby joints are left unfilled ; or to piping causing defined channels in which the pressure is increased. It may take place very rapidly, and then cannot be delayed by repairs, but it may stop of itself. As soon as practicable, remedial measures should be taken—probably the best of these is to extend the upstream apron and thus reduce the pressure downstream.

Regulators on alluvial soil should be secured from uplift by, or creep of, percolation water by being carried on long platforms which thus perform the same office as the extended base of an alluvial weir. As in the case of such a work, a regulator should be furnished with curtain and core walls to cut off subsoil flow.

Cross-drainage works should be securely founded, and if necessary, protected from creep of water by curtain walls upstream and downstream, and they should be provided with staunching walls, forks and rings as described in Chapter XXVII.

River flood embankments and canals should have preventive arrangements made to stop percolation, as noted on p. 114.

CHAPTER XVII.

LOSSES OF WATER.

THE various losses of water which occur on irrigation works are so considerable that every precaution should be taken to lessen them, in order to increase the net balance which alone is available for irrigation. These losses may be classed as preventible or reduceable: under the first come wastes of every description, and under the second, evaporation and absorption. It is first necessary to consider the causes of loss, and thereafter to devise measures to prevent or diminish them as much as may be done.

Wastage may be due to defective construction or careless maintenance; the former is direct and should be reduced by sound location, design and execution of the works and will be dealt with first; the latter is indirect, as it acts by increasing evaporation or absorption, or both together, and will be discussed under those heads. A reservoir basin should have an impervious bed (see p. 142), seeing that it occupies a large area under considerable pressure. Excavation of material in it should therefore not be carried so deep as to disclose pervious strata; but everywhere there should be an impermeable cover which in course of time will be rendered more staunch by the deposition on it of silt. A uniformly porous bed will lead to absorption, the amount of which will depend partly upon its vertical and lateral extent, but, chiefly, on its degree of porosity. If the substrata are impervious and rise above full-supply level on every side, the loss on this account will be a minimum one, and consist principally of the amount required initially to saturate the porous volume. Even if impervious strata are deep-seated or non-existent, the abstraction of water underground in uniformly porous formations may not be excessive, seeing that its rate of travel is reduced by the considerable friction which occurs during subsoil flow. A great source of loss is a fissured bed, as that will lead away a large amount of flow which will not be much retarded by such friction. The greatest loss will occur if the fissured material is soluble, as in the case of the dolomite formation, for then the water passages may enlarge and may be made to communicate with neighbouring, similar, large subsoil areas. Careful geological examination is therefore necessary in doubtful cases to determine what is the actual state of affairs. If a large extent, or degree, of porosity is disclosed, and especially if the substrata are found to be fissured, the storage site should be abandoned.

A dam must of course be securely founded. If it is a masonry one, all fissures below it should be filled, with cement concrete, if wide, or by cement grouting, if narrow. If it is an earthen one, a puddle trench of substantial width should be carried down to sufficient depth to prevent any appreciable amount of leakage, which, owing to the frictional loss of subsoil flow, will usually not be great, 30 feet or somewhat more below the surface in fairly uniform and watertight soil. Dams, if properly constructed of suitable material, are practically impervious. Similar remarks to those made with respect to the reservoir basin apply to the soils through which canals are led, and for them porous and fissured formations should be avoided. Particular care is necessary to make cross-drainage works watertight and their junctions with the canal earthwork staunch. The largest amount of wastage from canals occurs at outlets, if these are numerous and defective in construction, and along field watercourses irregularly aligned and badly maintained.

Evaporation from water surfaces is affected by the dryness of the air, the temperature of the water and the movement of the air ; a strong, dry, hot wind has the greatest effect in this respect. Naturally, the total amount of loss from it depends greatly upon the area exposed to its action. Thus, although the vertical rate of evaporation will be least in the cold weather and most in the hot weather, the amount of loss on storages will not vary proportionately to the temperature in the different seasons. During the first-named the surface area will be at its maximum and in the second named at its minimum, while during the monsoon, although the surface is considerable, the temperature fairly high and the wind strong, the air is naturally saturated with moisture and thus not highly absorbent, and the rain falling directly on the water surface will make good a large amount of loss from evaporation. Evaporation also takes place similarly from the surface of the ground ; its amount depends upon the degrees of the exposure of that surface to sun and wind, and of the moisture of the soil and of its capillarity, which allows subsoil percolation to be drawn up to the surface and to be evaporated in its turn. Lastly, evaporation takes place from growing vegetation: this is least productive of practical loss when the plants are deep-rooted and draw their supply from a level lower than that reached by the roots of ordinary irrigated crops.

Loss by absorption in canals results chiefly from the porosity of the soil, as noted above when dealing with reservoir basins. Such has been found to be greater in cuttings than embankments; to vary as the wetted perimeter and depth of the channel; to depend upon the porosity of the soils traversed; and to decrease as the time of saturation increases. This loss is a fairly constant one and does not fluctuate with the season, as does that from evaporation, except when the season affects the canal flow. It results in producing seepage, and if that is not deep-seated and can be intercepted, the loss on this account is not a final one, but the recovery of the water thus derived will entail expense.

The losses from evaporation and absorption are usually ascertained combined for reservoirs, seeing that it is difficult to determine them separately there: an allowance made for them in Bombay is equivalent to four feet in depth on the mean surface of the reservoir. Evaporation is usually measured in a small cistern, but such an apparatus, if immersed in a reservoir, would require to have its sides raised well above the water surface to exclude the waves, and thus would have its contents protected from the drying action of the wind on the crest of, and spray from, the waves. If the cistern were buried in the ground, the effect of the surrounding temperature would exaggerate the amount of the evaporation by, it is said, as much as 50 per cent. On canals such cisterns can be used with fair accuracy as wind action on their surface raises only shallow ripples. However, on them the combined loss is also generally taken into account, and is known as "loss in transit." On the Bari Doab Canal it was measured to amount to 20 per cent. down the main canal, 6 per cent. down distributaries, 21 per cent. in the field channels, and at outlets and by defective irrigation to 25 per cent., *i.e.*, to total 72 per cent. of the supply at the canal head, leaving only 28 per cent. as balance utilised for irrigation. The loss in transit is so great that it must be allowed for in designing the canal system; for this purpose the discharge calculations for the various sections have to be worked out first from the tail and to be continued upstream.

The total amount of all the losses enumerated above depends principally upon the time during which they occur, and the best way to reduce that amount is therefore to diminish that time, after making the works as staunch as practicable. In regard to reservoirs, the supply should be utilised as much as possible during the early part of the fair weather, and storage from one year should not be conserved as a balance to meet possible bad replenishment in the succeeding year, except in the case of town water schemes where continuous supply must be assured even at considerable cost. In canals water should be passed down as rapidly as practicable by alignments made as direct as may be, and in channels maintained in proper order; this especially holds good in the case of field channels where most waste takes place; leaky sections should be made staunch. In regard to actual irrigation that should take place by rotation (p. 70), and by the application of the measures described on p. 69.

To aid in devising methods to reduce losses, it is desirable to conduct experiments to determine their amounts, so that it may be ascertained if the proposed remedies will be justified by the economies likely to be effected. In regard to loss by evaporation and absorption in a reservoir, its original contents and also the amount drawn off for irrigation should be accurately measured: the difference will represent that combined loss. To determine that due to evaporation alone is difficult: if the reservoir has an impervious bed, the loss on this account will be small, and practically the total loss might be put down to evaporation. Where the bed is pervious, a small deep and sheltered arm of the reservoir might be partly shut off from the main body thus to form a still-water area (in which a gauging cistern might be arranged to float between vertical guides), and the evaporation loss thus directly measured. Observations should be made of the leakage from the dam and of the seepage from the canal system: also, of the total loss of transit in the latter, and of the amount of evaporation from it—the balance loss will be that due to absorption. At intervals, special gaugings should be made at stations all down the canal to determine where the greatest amount of loss takes place in order to lessen it. Experiments have been made in India to render canals staunch by various descriptions of lining, but there the largeness of the works and the smallness of the water rates make linings generally prohibitive in cost while few are effective. In America concrete, and in Australia asphalt, linings have been constructed, but at an expense only justifiable when the value of water is very great. Probably the cheapest way in India of securing staunchness, especially in alluvial canals, will be to excavate them of somewhat larger section than that necessary for their discharge, and allow them to silt up to the latter size.

CHAPTER XVIII.

ECONOMY OF WATER.

Water is the finished product of irrigation and therefore as much care should be taken to utilise it in the most economical manner as would be exercised in the case of the expenditure of money. If this is not done, the extent of the area irrigable will be reduced and the benefit from it to the cultivators and the country will be diminished. Economy can be obtained both in the construction, or design, and in the maintenance, or working arrangements, of the schemes. It has to be remembered that the ordinary irrigator is inclined to be lavish of supply under the mistaken impression that thereby he is increasing the out-turn of his crops and getting more value for his water rate. The contrary is frequently the case, for over-irrigation may leach some of the manurial constituents out of the soil and may sour the land by depriving it of aeration ; for both these reasons it may diminish the weight of the produce. The cultivator should therefore be educated to see the advantage of using the minimum amount of water required to develop his crops and of control of supply in the general interest. Such control is absolutely necessary during seasons of deficient discharge, and to make it then most efficient the irrigators should always be accustomed to it, so that they may appreciate how it secures impartial and fair distribution to them.

In regard to construction a reservoir site should be selected where the basin is impervious and the dam can be founded on a watertight stratum. If the reservoir usually fills and runs to waste, monsoon irrigation should be encouraged so as to take advantage of the surplus yield : this area may be extended by constructing high-level channels a little below full-supply level, so as during the rainy season to increase the command near the source of supply. The irrigated area should be concentrated and as close as practicable to the headworks—reservoir or weir—in order to diminish loss by transit ; it should not be underlain by highly porous strata extending nearly to the surface, nor traversed by deep water courses, as both of these will induce loss by seepage. The canal system should be aligned so that water may be brought on to the fields by the shortest course possible. The irrigation channels should pass through impervious soils so as to be watertight (see p. 66). Where this is not feasible, excessive leakage through sandy soils or fissured strata should be diminished by waterproofing devices—lining or puddling the canal, or forming puddle trenches under its downstream bank. The velocity of flow should be the greatest which the natural soils can stand without erosion, so as to reduce the sectional area and thus the amount of absorption and period of flow, as well as the cost of the excavation. All these arrangements, by lessening the loss in transit, will increase the irrigating capacity of the work : that loss between the headworks and the irrigated area may be nearly half the initial supply and should be susceptible of considerable diminution.

Losses of water may either be unavoidable or controllable. Of the former the principal is evaporation from the surface of reservoirs, which during the whole year may amount to four feet or more on the mean area exposed, and is thus very considerable. To reduce this loss the supply should be utilised as much as practicable during the early part of the fair weather when evaporation is at its minimum. The reduction of supply in the hot weather, when this loss is at its maximum, will be possible if in the irrigated area there are wells which can be drawn upon to supplement the canal supply. The area of perennial irrigation should be concentrated and the cultivation of isolated fields of such crops should be discouraged. Even if this leads to some loss of revenue, it will secure the greatest total area under crops. In the case of irrigation direct from weirs on streams the areas under cultivation in different seasons will naturally depend upon the then flow, unless the headworks are made into storage weirs to impound supply during, or soon after the close of, the monsoon for subsequent utilisation. For controllable waste the measures to be adopted during construction have been noted above, but others are necessary to prevent avoidable waste during the working of the system. The principal of these is connected with the field channels which may be badly maintained and worked and have leaky outlets ; these combined may uselessly consume one-quarter of the total supply admitted at the headworks. The remedies are to reduce the length of these channels and the number of the outlets as far as practicable, and respectively to keep them in good régime and watertight.

In comparatively modern times the most effective reduction of loss has been secured by working in rotation the minors supplying the field channels, and in seasons of scarcity the branch canals and distributaries alternately (pp. 66, 74): this system has the advantages described below. First, administrative control over distribution is obtained by superior authority and with a reduced canal staff. Then the proper régime of the channels is maintained by running them full, or nearly so, during their period of flow, so that this takes place with the designed velocity and thus reduces silting. Moreover, while the channels are dry, losses by seepage and evaporation do not occur. The convenience of the irrigators results from the non-interference by the subordinate staff, as regulation of the outlets at the head of the field channels becomes unnecessary, since all are entitled to flow full while water is being passed down. Leakage from the outlets out of use cannot take place, and dribbling discharges at the tails of then closed minors are obviated. Unauthorised irrigation during the rotational periods of closure is prevented, and fair distribution is secured for all irrigators from the head to the tail of the minors in flow. To gain the greatest benefit from rotation the depth of individual waterings and the intervals between them should be regulated so as to limit the supply to the crops to what is sufficient and to reduce the losses by evaporation and absorption.

To enable the superior staff to control the expenditure of water it must be furnished with data of the supply available. In the case of reservoirs the amount of storage at the end of the monsoon should at once be ascertained, and in accordance therewith an estimate should be prepared of the monthly levels down to which the storage may be drawn, taking into account the irrigated area practicable, the duty of water and the loss by evaporation. For the working of channels time tables of closures should be prepared to secure proper rotation; to prepare these frequent gaugings of the actual discharge from time to time should be made and reported promptly to the controlling officer.

The assessment of irrigation water by measurement of the quantity supplied (see p. 34), and not of the area irrigated, has been strongly advocated as the most economical system. Another method is to sell water to irrigators at volumetric (or bulk) rates. The first system has been carried out successfully in Italy and the second in Spain, but in India they may not be equally adapted to the less advanced irrigator, who may be inclined to dispute the measurement but not the area. Moreover in tropical climates the value of a unit of water fluctuates much more than it does in temperate ones, owing to the great variations of the supply available. It is highest in seasons of drought, when a uniform rate would not pay the State sufficiently for the then value of water. It is lowest in good years, when such rate would be too high and its imposition would retard the expansion of irrigation. In India careful supervision of irrigation is the best means of preventing waste and economising supply.

CHAPTER XIX.

DUTY OF WATER.

THE duty of water is an expression used to denote its irrigating capacity, either as estimated before a scheme is carried out, or as ascertained by the actual results secured when that is in operation. There are two main classes of duty—"flow" and "quantity." The first indicates only the rate, while the latter takes into account the total amount of consumption of water; the former will equal the latter if it is multiplied by the time during which irrigation continues, and this is called the "base" of the duty. There are various ways in which duty is expressed in different countries, according to the units adopted, but the general result is the quantity consumed, either in the time or total period considered, and this enables comparison of the differently stated duties to be made. The flow duty is a factor for determining the size of the canal, and the quantity duty one for settling the amount of supply required either from natural discharge or from artificial storage.

The principal factors on which duty depends are as follows. The method of cultivation, including tillage and irrigation: this is what rests upon the skill and care of the irrigator, and when properly conducted, tends to the progressive increase of the irrigated area: the education of the irrigator in this respect is thus of the greatest importance. The next factor is the nature of the soil on which storage is effected, through which the canal is led, and to which water is applied for irrigation. Such matters must be considered before the works are started so as to gain the best natural conditions: here also improvement should gradually occur as all the areas concerned will improve in retentiveness as silt is deposited on and penetrates into them. Climatic conditions greatly affect the duty: they vary from year to year and are not susceptible of improvement by man, but he can select beforehand the most favourable situations for his works. Still, betterment will be produced by a large extension of irrigation which will cool and saturate the air and ground, and thus may lessen evaporation and increase precipitation of rainfall. Canal conditions have also an important effect—rapid flow in the canal, concentration of the irrigated area, rotational supply and a system of payment encouraging economy of water will tend to development, while their opposites are likely to retard that. Some of these conditions should be attended to when designing the project and others during its operation. Care should also be taken to deal with water containing fertilising matter. Lastly, the species of crops grown will cause variation in consumption of water. Although crops will be selected principally to suit the character of the soil and the demands of markets, the administrator by varying the water rates can obtain the best value for the water supplied, without, however, interfering with the irrigator unfairly.

Another cause for variation in duty results from where the observations for it are conducted. If water measurements are made at the source of supply, the duty will be decreased by the loss in transit to the irrigated area ; if they are carried out near the head of that area, such loss will be greatly reduced and thus the duty will nominally be much increased. Both sets of observations are however desirable, the first to determine the total amount of supply required and the loss which occurs (with a view to lessening it, if practicable), and the second the quantity wanted for actual irrigation (so as to enforce due economy in consumption).

The factors influencing duty are so various that it differs on every work, and sometimes on sections of the same canal system. It is therefore difficult to predict its amount except by comparing a new scheme with an existing one in the neighbourhood under similar general conditions ; it is to enable this comparison to be made that duty experiments are so valuable. Moreover such experiments, continued for many years on the same work, indicate if proper economy in distribution is taking place, and due increase of the irrigated area is being attained by progressive improvements both in control and in cultivation.

The water supplied for irrigation is utilised in producing crops or is lost by evaporation and absorption. The crops require supply to enable their roots to obtain nourishment from the land and to provide for evaporation from their leaves during the process of growth. If that supply is over-stinted, the out-turn will be reduced, but this rarely occurs ; it is well-known that a comparatively small amount of irrigation generally gives the best results, and, in particular, leads to the development of the more valuable part of the plant and to the reduction of the less useful part. Thus it has been proved by experiment that over-irrigation of wheat tends to increase the amount of the straw and proportionately to lessen that of the grain. After every watering the evaporation from the ground is considerable, therefore waterings should be deep and few on retentive soils, and on them a proper tilth should be preserved to diminish such evaporation. Absorption into the soil not only causes waste of water but thereby carries away from the crop some of the fertilisers used to stimulate it : sandy and porous soils should thus not have heavy waterings, but may be given more frequent light ones as they lose less from evaporation than impervious ones. In India a heavy watering varies from 0.33 to 0.25 foot and a light one from 0.25 to 0.20 foot. The rise of subsoil water, or the flow in watercourses produced by seepage, are sure indications of excess supply, and that should then be reduced in amount. By attending to these precautions the duty may be increased, and at the same time the crops benefited.

As explained on p. 70, one of the best means of increasing duty is the adoption of a system of rotation of supply in the various channels, and that lies in the hands of the canal administrator. Rotation is economical at all times, and during a period of scarcity is essential. In this latter period it is most desirable to ascertain the maximum duties attained without detriment to the crops, so that somewhat smaller duties may be aimed at in ordinary circumstances. In order that proper observations may be made of duty, it is advantageous on large irrigation schemes to have experimental stations under skilled supervision, and to explain to the irrigators the economy of water thus effected and the resulting benefit to the crops. The cultivator, although usually a simple husbandman, understands the value of what increases his profits, for on them his livelihood depends. An ocular demonstration of how to obtain a better out-turn will appeal to him much more than simply discussing the subject, which he may consider more theoretical than practical. Even with such a demonstration, owing to his conservatism, he will doubtless see difficulties ahead, and one of these is likely to be the increased cost of cultivation entailed by a strictly limited water supply : as a justifiable reward for practising economy his water-rate might be reduced. Immediate progress in this matter must not be expected, as development of improved methods will be slow. It is therefore not advisable when making new projects to assume too high rates for duties: if greater duties are subsequently obtained, the schemes will thus prove more remunerative than anticipated when making their forecasts, and the development of irrigation by other projects similarly worked out will thereby be encouraged. Too sanguine expectations in this respect are likely to have the reverse effect.

CHAPTER XX.

DRAINAGE.

DRAINAGE is necessary when lands are liable to be flooded, to become water-logged by the rise of subsoil water, or to be injured by the efflorescence from subsoil salt. Often the need for it is an indication of over-irrigation, and it may then be reduced, or avoided, by lessening the supply of water to the fields, or the extent of the area irrigated. Apart from flooding, drainage is required on account of seepage, or percolation, in excess of what the natural subsoil drainage can carry away. As drainage is an expensive addition to the cost of a canal, measures should be taken to obviate it if they are practicable.

Where there are numerous wells in the irrigated area, the rise of subsoil water should be observed by keeping records of the surface level of the water in them. In the Punjab it was settled some years ago that when the subsoil water table was more than forty feet below the ground surface, irrigation of fifty per cent. of the culturable area might be allowed ; but when the spring level rose to within ten to fifteen feet below that surface, irrigation would be stopped, or allowed only for one crop in the year to supplement the rainfall ; and would be varied between these limits in proportion to the rise of subsoil saturation. Where there are not wells, the amount of seepage from the canal itself can be tested, and this will give a fair idea of the total quantity of subsoil flow at the irrigated area. For this purpose gauging stations should be made along the canal at every mile, or other convenient interval, and discharge observations conducted at them as nearly simultaneously as possible, These should be carried out after the canal wetted perimeter has practically attained its permanent rate of seepage, by having the canal supply maintained at constant and fairly high level for two or three days previously by regulation of outlet discharges. Where excessive loss of absorption is thus detected, the canal should be made staunch by lining, or water-proofing, to reduce it. In the case of a contemplated canal the probability of drainage being required, or not, can be estimated by observing what is the effect of heavy rainfall on the area which it is proposed to irrigate. Where the surface has fair slopes, is traversed by good natural drainage lines, and the soil is of a porous nature, artificial drainage will probably be unnecessary: where, however, the ground is flat, even and impervious, that is likely to be wanted.

If subsoil water rises to the ground surface in alkaline soil, it will carry salts with it, and these will be concentrated by evaporation so as to produce an efflorescence which is highly prejudicial to plant growth. If the soil is sweet, the rise of water by capillarity will fill its pores, thus depriving it of aeration and waterlogging it, and this also will interfere with the proper growth of vegetation. In inhabited areas such rise is injurious to the health of the population by carrying with it noxious subsoil gases and germs. In the tropics stagnant water forms a breeding ground for mosquitos which disseminate malaria; for that reason all such collections near dwellings should be drained. Flowing water has not this bad result, but unless its margins are kept free from obstruction, they may become stagnant. Such bad effects have occurred on so many canal systems, that many engineers consider that from the start of irrigation drainage works should be constructed, as these will be a remedy for them. However, as prevention is better than cure, the first step to take is, as noted above, to keep a watch on the rise of subsoil water, and to stop, or retard it, by limiting the supply of water or the area to which it is applied for irrigation. Even if these measures are not successful, time will have been gained and information will have been obtained as to the probable amount of drainage which will have to be provided. That amount cannot, however, be exactly estimated beforehand, as it depends not only on subsoil and surface conditions, but also on the regulation of irrigation. Instead, therefore of starting at once with the excavation of drains, it is better to lay out their proposed lines, which will usually be along valleys, and to reserve sufficient land for them at first, but not to construct them until they are actually wanted. When this occurs the drainage system should be gradually commenced, and should be developed somewhat in advance of requirements by increasing the length and section of the drains as may be necessary.

The drainage system consists of main and branch drains. The former are the arterial lines and should have a continually increasing section sufficient at any point to carry the average discharge passing it; that discharge will be a fairly steady one and practically equal to the total average discharge of all the branch drains entering it. The branch drains deal with individual small areas, and thus have an intermittent flow corresponding to the progress of the actual irrigation of those areas. In addition to disposing of flow due to irrigation, all drains must be able to discharge storm flows concurrently. In Egypt, a rainless country, main drains are designed to carry one-third, and branch drains one-half, of the irrigation supply to the areas served by them. These considerable amounts show how necessary it is to economise that supply, for not only is the water thus wasted, but also much of the dissolved constituents of the manure applied to stimulate growth may be lost. The large discharging capacity of the drains moreover involves considerable capital expenditure and maintenance cost, so much so that in certain cases it has been found impossible to finance a perfect drainage system. When this happens, some parts of the scheme may have to be sacrificed, but on no account must the outfall arrangements be curtailed. An outfall must be properly designed, aligned and constructed and must always be maintained clear and unobstructed, for, even if it is only partially blocked, all the drains upstream may be interfered with and their discharging capacity lessened. Such blocking will take place during and after heavy rain if the bed of the drain at the outfall is below the high-flood level of the natural drainage line into which it discharges. Swamps are produced at depressions without outfalls, or by impervious barriers blocking what should be their outlets; where such occur below a canal, they should, if possible, be drained and this may be practicable by a drain through the enclosing high land or a cut through the barrier.

Drains should be aligned, constructed and maintained as carefully as canals. Their course should be as direct as possible and their gradient and velocity as great as the ground will stand without erosion: their cross section should vary from point to point so as to be sufficient to carry their discharge. The inflow of lateral muddy flows should be prevented by small side banks so that the drains may not have surface silt brought into them. As drainage water is clear, sunlight penetrates it, and thus causes a luxuriant growth of weeds, which, if not removed, retards the flow, and leads to obstructions being deposited on the beds. Drains should therefore be deep so that they may be shaded even when they are running full. To prevent water-logging, and the rise of subsoil salts, their full-supply level should be at least two feet below ground surface.

The internal drainage of large earthen dams is described on p. 107. Main downstream drains should be deep so as to carry off low-seated subsoil water. It is advisable to fill in such drains with rocky *débris* from the excavations of the works which should be arranged with the larger particles at the base and the smaller at the top: this filling should be cased by fine insoluble material nine to twelve inches thick to prevent the ingress of earthy matter, and should be covered over by two feet of soil carried a little above ground level for the same reason. Such drains will continue to run clear as their sides cannot fall in, surface silt cannot be brought into them, and vegetation cannot grow in and choke them. Surface drains downstream of dams should be open excavations and should be carefully maintained. The discharges of all drains should be gauged over notch boards and recorded; as time goes on, they will probably decrease greatly owing to the silting of the reservoir bed and the consolidation of the dam and its seating if that is of earth. Any sudden increase of discharge should at once be inquired into it: if the flow becomes turbid, it is an indication of a leak being in process of formation, and immediate measures should be taken to staunch it at its source. The condition of the ground downstream of the dam will indicate how the drains are working: if it is dry, it will show they are all efficient; if it is wet, that some, at least, are defective and that these should be attended to. Wherever practicable the tail channel of the waste weir should have its bed lower than the beds of drains discharging into it so as to form a clear outfall for them. If the former at the natural junction is at the same level as the latter, the *débris* which it brings down will choke them; to avoid this the tail of the drains should be diverted to obtain a clear outfall downstream.

CHAPTER XXI.

HYDRAULIC GRADIENTS.

THE hydraulic gradient of an irrigation work may be defined to be the surface slope of the percolation water which passes through or under it. At any point on the base of the work the height of this gradient above it indicates the amount of upward pressure exerted there by that water. The slope of the gradient determines the rate of the subsoil flow. Irrigation works should therefore, be designed to keep the hydraulic gradient as low as possible, so as to reduce the internal upward pressure, and as flat as practicable, so as to diminish the rate of subsoil flow, in order that it will not carry away any particles of the foundation whereby the work would be undermined. The slope of the hydraulic gradient depends upon the levels of its head and tail, and the distance between these: designs of works affected by it should therefore provide that the calculated slope is not increased, or undue velocity of the subsoil water may occur. The head level and the length of the slope are settled by the design, but the tail level taken into account will decrease unless a fixed plane is found for it, and that is the minimum level of the natural water-table of the ground at the point where the percolation water meets it, or the lowest level at which that water issues from the work. Should the tail level fall to a level lower than that assumed for it, the gradient, and thus the rate of subsoil flow, will increase, and danger to the work may ensue. Should it rise to a higher level than that calculated upon, the rate of subsoil flow will contrariwise diminish, and the work will be all the safer from undermining; although upward pressures will thus be somewhat increased, they can be resisted by strengthening the superstructure. The design, should, therefore, assume the lowest tail level probable. If the percolation through such a work as an earthen dam or embankment is considerable, the water-table may rise to, or nearly to, the surface of the ground: in river works the water-table will correspond to the surface level of the tail water in the river bed.

If at the base of the works there is an impervious projection downwards into soil of gradually increasing density, the subsoil flow will have to descend to pass it, and will thereafter rise to travel through the more pervious top stratum. The hydraulic gradient will thereby have its length increased by an amount equal to twice the depth of the projection. Upstream of the projection the gradient will not be altered, but at the projection there will be a drop corresponding to the increased length of the gradient caused by it. The whole of the downstream part of the gradient will thus be lowered, and the section of the work above it accordingly relieved by the consequent decrease of pressure. If instead the impervious projection is upwards into the superstructure of the work, it will block and thus head up the subsoil flow, thereby flattening the gradient upstream and steepening that downstream of it, thus increasing the upward pressure throughout the whole length of the superstructure, and the rate of subsoil flow at the tail. Where the tail, or exit, of the hydraulic gradient is due to free subsoil flow, its distance from the head, or inlet, will depend upon the porosity of the subsoil. The denser and more compact is the soil, the steeper must be the gradient to overcome the large amount of internal resistance to flow, and the nearer will the exit approach to the inlet. On the contrary, with highly porous soils the natural free exit will be removed further from the inlet. When, however, artificial conditions are imposed, such as by an impervious cover of sufficient length and weight over the subsoil, the position of the exit will be fixed at the downstream end of the cover, and the slope of the hydraulic gradient and the rate of the subsoil flow upstream will be directly independent of the constitution of the subsoil. These are the conditions governing the hydraulic gradient, and that works may be constructed safely, their design and construction must comply with them. How this is effected on certain classes of works will now be described.

In an earthen dam on the upstream side of the centre line the subsoil flow along the surface of the ground, where the soil is likely to be most porous, should be cut off by a series of foundation benches with foundation trenches at their bases, all filled with compacted, watertight earth : this will have the effect of somewhat reducing the hydraulic gradient by making the upstream subsoil flow take a lower course. The main resistance to that flow will be offered by the puddle trench along the centre line, which, on the assumption that the subsoils become more compact as they are lower, will increase the length of the hydraulic gradient by twice its own depth. If this trench passes through firm strata and is founded in still denser material, its depth need therefore not be excessive, and (from point to point on the longitudinal section) might vary from the amount of the pressure head of the reservoir above ground level for fair subsoils, to half that for good subsoils, especially if the base of the puddle trench is drained. The upstream part of the dam embankment should be formed of the most clayey watertight soil procurable, and this should be thoroughly compacted so as to offer the greatest resistance practicable to subsoil flow, thus steepening the hydraulic gradient. If the dam downstream of the puddle trench is underlain by drains, the exit of this gradient will be formed there, but owing to the flat upstream slope of the embankment, will not be advanced so near to the inlet as unduly to increase the rate of the subsoil flow. If, however, the dam is constructed of pervious material insufficiently consolidated and to too steep slopes, the exit of the hydraulic gradient might, at first, take place up its downstream slope. As there it would not meet with any resistance, it would tend to lower itself to the surface of the ground where the percolation would emerge; this might increase the steepness of the hydraulic gradient, and thus the rate of subsoil flow, to an extent sufficient to cause a slip. Where the dam is formed of pervious material, its slopes should therefore be flatter than would be sufficient were it made of impervious earthwork, so as to increase the length of the hydraulic gradient, and thus to diminish its slope and the rate of subsoil flow.

Masonry dams should, whenever possible, be founded on solid rock, the compactness of which destroys the hydraulic gradient and prevents subsoil flow. If such a work has to be built on fissured, but otherwise sound, rock, its foundations should be carried deep to obtain similar results, or, with the same object in view when the rock is not highly fissured, to a somewhat less depth with a good cut-off trench upstream, filled with cement concrete to lower the hydraulic gradient at its start and staunch the fissures at their head. Similarly, core walls at the upstream side of the foundations act so as to lower the hydraulic gradient, as well as to tie the dam on to its base and resist any tendency to slip. In this case a deep longitudinal drain just downstream of the dam will lead off any percolation water above the level of its base, and thus diminish the hydrostatic pressure, or uplift, on the dam.

River flood embankments on alluvial soil should have flat slopes, partly to increase the length of the subsoil hydraulic gradient, and, partly, to extend the gradient through their own material. The water pressure on the subsoil is the greater of the two, but its material should be more compact, and its resistance to flow can be added to by the construction of key trenches. The hydraulic gradient of the embankment will usually be the flatter of the two, and should be increased in proportion to the porosity of the bank by flattening the slopes as necessary. To steepen, and thus to diminish the length of the gradient, the embankment should be compacted by rolling. Canal regulators and sluices passing through such river embankments, or along the canals, are founded on long horizontal pavements with upstream curtain and core walls, which artificially increase the length of, and thus reduce the velocity of flow due to, the subsoil hydraulic gradient.

Weirs on alluvial rivers are designed with watertight upstream aprons (see p. 61.) staunchly united to the crest walls, so as to form the inlet ends of the hydraulic gradients upstream of the main works. Such an apron lowers the level of the gradient and thus reduces the consequent upward water pressure throughout the length of the weir. To increase the length of the gradient at the upstream end of the upstream apron, there should be a deep watertight curtain, and, for a similar object, the crest wall should also be founded deep. The downstream apron acts as an artificial cover confining the hydraulic gradient and extending its length to the tail wall. This should give a free exit to prevent any blocking of the subsoil flow, which, if it occurred, would raise the tail of the gradient, thus flattening it upstream, and increasing upward water pressure on the whole of the weir. The entire length of the weir, including the upstream apron, should be sufficient to produce a hydraulic gradient so flat that the subsoil flow will not carry away any of the sand foundation : the finer the sand, the longer should be this length. The further upstream are placed curtain walls, the longer is the length of the weir benefited by the consequent lowering of the hydraulic gradient. Every part of the weir must be amply strong to resist the upward pressure to which it is subjected.

Wells are also works depending for their supply on the hydraulic gradient producing flow to them in pervious homogeneous soils. The inlet end of the gradient is at the surface of the water-table, or plane of saturation of the soil, and the tail end at that of the water in the well. When the ground is highly saturated, the difference of level at those points will be small, the gradient short and flat, and the flow sufficient. As the saturation diminishes, the well water surface must be lowered by pumping, etc., to maintain the flow, and this it will do without altering the conditions if the percolation gradient remains at the original slope. If, however, pumping is excessive, the hydraulic gradient will be steepened, and the rate of flow to the well may then be unduly increased ; if particles of the soil are thus carried into the well, that may be undermined and caused to collapse.

CHAPTER XXII.

SILT AND SILTING.

For practically all irrigation works the proper treatment of silt is a matter of great importance: when they are situated in alluvial country it becomes one for supreme consideration, as there the engineer has to study, not so much how the action of water, but how the behaviour of silt will affect them. Silt is said to attract silt: that is, because the first deposits contract the area of the waterway, and at the same time increase the frictional resistance to flow; both these causes lead to further accumulation of the matters previously in suspension in the water. The questions involved in dealing with silt are so numerous that they cannot adequately be discussed in a single chapter, so that only its principal features and the best methods of treating it will be noticed here.

There are many varieties of silt. The deposit in reservoirs is of three physical descriptions—heavy detritus, which is dropped by floods as soon as they enter the head of the storage; heavy silt, which remains in suspension for some time but is eventually precipitated; and fine silt, consisting of flocculent earthy matter, most of which very slowly gravitates to the bed, while the rest is discharged through the outlet of the dam. More generally, silt may be said to consist of all matter, both inorganic and organic, brought down by stream flow: it thus includes boulders, pebbles, gravel, coarse and fine sand, clay and earth, and also, drift timber, bushes and animal *débris*. If derived from the washing down of the catchment area, it may be called "original silt"; if produced by the scour of the bed or erosion of the sides of the channel, it may be termed "local silt." Inorganic silt may be classed as "soluble" or "insoluble silt"; organic silt will eventually, after decomposition, be chiefly soluble. Only the soluble variety fertilises the soil, and as much of it as possible should therefore be brought on to irrigated land, where it will take the place of artificial manure. As the insoluble kind, if deposited in the irrigation channels tends to choke them and to interfere with their régime, and if carried on to the fields to render them sterile, the engineer should endeavour to admit as little into, and to pass early as much of it as practicable out of, the irrigation system. Lastly, silt may be divided into " bed silt " which is deposited in channels, etc., and " suspended silt " which is discharged on to the fields.

The amount of silt brought down by rivers depends upon the physical characteristics and meteorological conditions of their catchments. Its distribution along the course of a river varies with the nature of the flow ; where the velocity is checked, silt is deposited, and where that is accelerated, it is carried away. Turbid waters tend to cause accumulation of silt, and clear ones its removal : the entry into irrigation channels of the former should therefore be prevented as much as may be, and the admission of the latter encouraged to improve their régime. As the quality of water in this respect cannot be judged by eye, the nature of the sand suspended in it should be determined by analysis, for which purpose samples of the sand should be dropped into a vertical tube filled with water and terminating in a glass measure. The velocities at which the first and last grains fall are noted and the sand classed accordingly. Except where the flow is very turbulent and the bed silt is thus carried up to the surface, the silt is not uniformly distributed in a volume of water. The finer particles are alone in suspension near its surface, and the proportion of the coarser ones increases according to the depth. Water admitted into a canal should therefore be taken from the upper layers, and at a site where the river flow is regular and gentle.

Reservoirs have their storage capacity reduced by the silt derived from their catchments : the larger these are, other conditions being the same, the more silt is deposited. Care should be taken for this reason not to construct dams where the drainage areas are excessively large compared with the amount of water to be impounded. More silt is produced by steep slopes, bare or tilled surfaces, and friable or soluble soils ; and less silt by gentle slopes, surfaces covered with vegetation (especially grass and trees), and hard or insoluble soils. The nature of the catchment should be examined and one likely to yield much silt should, if possible, be avoided, or improved in this respect by afforestation. In the tropics most of the silt is washed down at the beginning of the flood season, both because the rainfall is then intense, and because the surface has been desiccated during the preceding dry and hot weather. As it would be too expensive to remove silt by excavation, endeavours should be made to prevent its deposition, and that can best be done by passing the early turbid flows out of the reservoir as rapidly as possible through large undersluices. By thus keeping the reservoir basin small, less time is given for the inflowing stream to precipitate its suspended matter, and more opportunity for it to erode and transport previous heavy deposits, which will thereby be moved nearer the discharging outlet, and may finally be passed through it. The chief objection to silting is that it continuously diminishes the storage of the reservoir, whereas the demands of irrigation on that should steadily increase. On catchments which from their their size and nature of surface will not produce much silt, this reduction of storage will be slow, and will become slower as the capacity is diminished by previous deposits. Eventually in their case, and sooner in that of heavily silting ones, the restoration of the original capacity will become necessary, and that is most easily carried out by raising the full-storage level of the reservoir.

Alluvial rivers are greatly affected by the silt they bring down. The largest particles of sand with highest specific gravity and most angular shape are deposited in the upper reaches ; and the finer, the lighter and the more flaky are the particles, the further are they carried down, until eventually at the delta pure mud is precipitated. A rising river charged with silt, silts up low places *in its bed ; a falling river with a deficit of silt will scour and* deepen the bed. At shallow places where the velocity is reduced, and just below caving banks, where there is an overcharge of eroded material, silt is deposited. Where the velocity is increased, as below a cut-off at a horse-shoe bend, or as below a bar across the bed, silt is picked up and carried forward. The silting of one part of the cross section causes increased velocity and thus scour in another part of it: this action occurs chiefly at curves, which are thus places where the course of the river is liable to change and therefore unsuitable for the construction of a bridge or weir. It is only where the river course is straight, and its bed and banks are hard and silt is neither in excess or deficit, that the best permanent sites for work can be secured. The design of weirs and bridges depends upon the nature of the sand upon which they are founded : as sand is continually moving down the river, the most unfavourable material within five miles upstream of the site should be determined and taken into account. If such weirs are constructed of length excessive for ordinary floods, their backwaters are liable to silt up irregularly owing to the slowness of the current, and to form islands which will mask the part of the weir below them, and thus render the flow over the whole irregular and productive of cross currents which may endanger the work. The best remedy for this is the provision of sufficient undersluices to deal with the additional discharge of larger floods.

In non-alluvial canals silting is usually not excessive ; if not considerable, it can be disposed of by harrowing the bed and by flushing with the clear water available ; where much occurs excavation may be necessary for its removal. Alluvial canals are subject to heavy silting : this has to be reduced before its admission, or dealt with after its entry : the former is the better arrangement of the two, and is effected—by drawing off the clearer supernatant water ; by passing the inflow through a silt trap above the weir which is flushed as frequently as practicable by the undersluices (it has indeed been recommended that these should be kept open throughout the flood season) ; by having wide head regulators to reduce the velocity of inflow ; by working the undersluices and head regulators alternately to prevent silt being churned up and carried into the canal ; and generally by shutting out very turbid water. Supernatant clear water can be arranged for on canals with permanent heads by raised sills at the head regulator : although this cannot be done permanently for inundation canals with head regulators miles away from the river, it may be imitated for them by temporary silt regulators constructed near the river bank. Admitted silt should, if possible, be passed out of the system at silt escapes : other devices for dealing with it have not been very successful. The experiments of the late R. G. Kennedy, C.I.E., have resulted in his theory which has revolutionised the design of canals in India, by adjusting the gradient and depth so as to secure a rate of flow which is at once non-scouring and non-silting. This improvement does not, however, diminish the total amount of silt admitted but keeps the maximum amount in suspension for the longest time, thus enabling excess to be passed out at escapes or at outlets. It therefore tends to lessen deposit in the main channels, but to increase it in the water courses and on the irrigated lands. In canals silting is more objectionable than scouring ; the former entails continual expense on maintenance, whereas the latter can be dealt with, once for all, by reducing the gradient by means of vertical falls.

Cross-drainage works are also affected by silt. If it occurs irregularly or excessively, it may block their waterways to a dangerous extent : such waterways should therefore not be too low nor narrow. It is generally best to pass a heavily silt-charged flow above a lightly charged one. Where much silt has to be discharged, a high velocity should be allowed.

In what is written above silt has been regarded as a nuisance which has to be got rid of, or avoided at considerable expense and trouble. It is, however, in certain cases a benefit of which advantage should be taken. In reservoirs a moderate amount of clayey deposit waterproofs the bed without much diminishing the storage. By its penetration into alluvial weirs they are rendered more staunch and stable. Canals can also be waterproofed thereby, while by forming silting berms and banks they can be strengthened and raised, thus increasing their irrigation command which is of much use in flat alluvial country. Waste land can be levelled for irrigation and fertilised by a system of colmatage, or warping, in which silt is deposited thereon. Alluvial rivers and irrigation from them greatly improve the cultivated area by bringing sweet silt on to it, which is the best remedy for dealing with salt efflorescence.

CHAPTER XXIII.

ASSIMILATION OF FULL-SUPPLY AND HIGH-FLOOD LEVELS.

THE two principal superior levels of a reservoir are those of its full supply and of its high flood. The former fixes its normal full-storage capacity, and the latter provides for its abnormal rise during the heaviest floods. As the dam must be safe under the severest conditions by which it may be tested, it has to be raised, beyond what would suffice at full-supply level, by an amount at least equal to the depth on the weir crest of the highest flood anticipated. Since the cost of dams rapidly increases with their height, this essential provision for safety involves a large amount of expenditure, which, in ordinary designs, may be looked upon as the insurance paid to obviate dangers to the works and to interests which might otherwise suffer. An increase of storage level also augments the amount of water impounded, and to a very considerable extent, seeing that the top contours of a reservoir greatly exceed in area that of lower contours. The absolute necessity for raising the dam so as to be quite safe at high-flood level may thus be regarded, in ordinary designs, as involving a large addition to its cost, and as impounding, only temporarily during the continuance of the flood, a large amount of storage which has thereafter to be allowed to run to waste. It is therefore obvious that, if this temporarily increased storage can be maintained until it is consumed by the draw-off for irrigation and by the losses which will then occur, the modified design of the works which secured it will enable a much larger area to be irrigated, and for the extra cost entailed will probably produce a most remunerative addition to the revenue derived from the scheme, if limited to its permanent storage capacity. As compared with the figures relating to the original permanent design, the percentage increase of the temporary storage is fairly certain to be greater than that of the cost of the alteration of the works required to obtain it; the original percentage rate of revenue return will thereby most likely be increased by the modification of the scheme. Estimates will show how the remunerativeness of the project will thus be affected.

A difficulty which at once suggests itself is that, should the temporarily increased storage be either partly, or wholly, impounded, and another flood then comes on top, it may rise above the calculated high-flood level and unduly strain, even if it does not wreck, the dam. A design to raise the storage level temporarily towards the end of the flood season must provide for this contingency, as it is obvious that safety must never be risked.

An ordinary weir with a level crest and constructed solidly throughout has to pass off, at or near high-flood level as fast as it arrives, any flood that may enter the reservoir, and therefore its design does not take full advantage of the property possessed by storages of flood-absorption as the surface of the water rises. It has finally to deal unaided with such a flood, and to enable it to do this its length has to be made a maximum one, and thus its cost is increased. As a flood comes part of it is consumed temporarily by raising the surface, thus increasing the contents of the reservoir, and part of it is discharged by the weir at the level attained: the former effect is that which is called "flood absorption" (pp. 46, 140). The higher the maximum flood depth permissible over a weir, the greater is the amount of flood absorption. It is, however, usually advisable not to allow a great depth of water to pass over a weir, owing to the excessive pounding action of heavy discharges on the foundations, and therefore in the case of a level-crested weir the amount of flood absorption is limited. Moreover, as just stated, advantage is not finally taken of this property by such a weir, although at first it serves to retard the rise of the reservoir and to reduce the depth passing over its crest. To secure the greatest amount of flood absorption the surface of the reservoir should be "restricted" to a low level before a flood arrives, and should be lowered to that level after the flood ceases, so that the storage may regain its flood-absorptive capacity. A design which properly utilises that capacity must therefore take into account the total volume of a maximum flood, as well as of its greatest intensity, or rate of flow.

Having thus explained the general conditions involved by the assimilation of the full-supply and high-flood levels of a reservoir, it is necessary to describe shortly the main features of designs whereby that assimilation can be effected. In the first place, for the storage to gain large flood-absorptive capacity, large discharging power at a low level should be provided. For this when the dam is of earth, special deep-seated sluices are required to restrict the surface level during the early part of the flood season; when it is of masonry, the usual undersluices with sills not much above river tail flood level will be ample. To enable the waste weir to deal safely with a flood when temporary storage has been partially effected, its permanent crest should be constructed, say, four feet below high-flood level. On it should be raised a temporary crest of shutters of the same height, which, if not automatic in action, should be quick-acting. Lastly, when the temporary crest is non-automatic, special automatic sluices, say, eight feet deep, should be provided so as at once to discharge a large volume when the reservoir surface begins to rise above high-flood level.

To work the design properly the reservoir level should be kept as low as practicable by means of the undersluices during the early part of the flood season. Later on, when increased storage has to be impounded, the undersluices should be regulated so that the reservoir surface rises slowly, and so that the reservoir flood-absorptive capacity is only gradually reduced. Lastly, the time will arrive when the complete temporary storage has to be secured, and then the undersluices will have to be closed, the automatic gates made ready and the weir crest shutters fixed. Until this period comes, the reservoir compared with one having a level solid waste weir, will have increased safety, seeing that its water surface will be kept low between floods: thereafter, this increased safety will be reduced and dependence will have to be placed on superior skilled supervision, which, however, need be maintained only for a short time at the close of the rainy season. The whole system is thus best adapted to streams with unfailing yield during the flood season and a considerable flow for some weeks at its close, which will allow the temporary storage to be then effected. Where, however, these conditions do not obtain, it will be necessary to increase the undersluice discharging capacity to deal with floods which may arrive after the reservoir high-flood storage has nearly, or quite, been secured. The system may be of great utility in the converse instance of a reservoir which has to be maintained normally at a certain level and must not rise above it during a flood; such a reservoir might be in an urban or other area which must not be further submerged. The great weirs with temporary shutter crests and undersluices of Upper India show how this may be done. The system is not applicable in cases where there is little margin between the full-supply and high-flood levels, and where the high-flood discharge of the stream is large compared with the full-supply contents of the reservoir, as in both cases its flood-absorptive capacity will be small.

In order to assist in designing reservoirs so as safely to take advantage of their sufficient flood-absorptive capacity, the following rules are suggested :—

1. During the rise of the reservoir, the rate of the flood disposed of hourly by the absorption in the reservoir, combined with the discharge from the undersluices, waste weir crest and outlet, should be equal at least to half the calculated rate of the high-flood discharge of the catchment.
2. During the whole rise of the reservoir to calculated high-flood level, the flood thus disposed of should be equal at least to the total calculated amount of the maximum flood anticipated from the catchment.
3. The combined discharging capacity of the sluices and open crest of the waste weir and of the outlet at high-flood level should be equal at least to half the rate of the anticipated maximum flood discharge of the impounded river.

These rules take into account the capacity of the reservoir relative to the size of the catchment, and the rate of discharge and total amount of the anticipated maximum natural flood. They also provide for a considerable margin of safety by implying that the restricted level of the reservoir at the commencement of the flood shall be much below its high-flood level. The rise of surface will then be lengthy, owing to the absorption of most of the flood in the reservoir, and the discharge of the balance out of the reservoir. Ample time will thus be secured for dealing with floods, for, as soon as one is expected, the reservoir surface can be lowered rapidly before the flood attains its maximum discharge.

The advantages of this form of weir with deep-seated undersluices, removable crest, etc., are many and are shortly described below. It provides for the reservoir being kept at a low level for most of the flood season, when floods are most intense, danger is greatest and repairs are most difficult. It allows the reservoir surface to be lowered quickly at any time when necessary. It passes the heavily-silted early floods out of the reservoir rapidly, and the deposit on the bed will then be reduced: larger catchments may thus be utilised without excessive silting taking place. It brings the flood-absorptive capacity of the reservoir fully into play, and thus converts short-lived large floods into long-lived small ones, which will affect the works less prejudicially. It enables the weir to be greatly shortened, and is thus eminently adapted to sites with a restricted length (see p. 116.) As it conforms to the usual varying levels of the natural longitudinal section of the ground, it permits a great variety of sites to be advantageously adopted for the waste weir; moreover the deepest part of the weir may be utilised for an outlet. It directs the tail flood of the weir down a defined channel, thus obviating costly protective works. Although this type of weir is best adapted to countries where there is a regular flood season, and ones subject to heavy floods at intervals, it can be applied in others where the conditions are the reverse.

Notwithstanding that a level, solid waste weir does not secure any of these advantages, it is generally preferred because it is looked upon as automatically safe: this, however, it will not be if its length has been underestimated, or the work is visited by an abnormal flood, seeing it is impossible then to increase the discharging capacity except to a very small extent by opening the outlet sluices. The initial discharges of even subsequently extreme floods are small, and their increase gradual, and thus there is ample time for lowering the reservoir by large undersluices to increase its flood-absorptive capacity. Further, the period during which alone the working of the weir requires skilled supervision (because high-flood storage has been impounded), is short, and occurs only at the end of the flood season when repairs can be effected. Now railways are operated throughout the year all over the world with practical immunity from disaster, although this may be occasioned at any time by an error in signalling of but a few seconds. Boilers and machinery with potential highly-destructive capacity, and electric installations with death-dealing power, are safely worked. Steamers are continually liable to being wrecked, and in aviation calamity awaits the flying machine if any serious defect occurs, as this may rapidly increase. Despite all this break-downs are of very rare occurrence; if their contingency were deterrent, progress would be stopped and civilisation would be at a standstill. The fact is accidents are not likely to take place when their possibility is foreseen and guarded against by necessary precautions and watchful care ; they are much more probable to happen when there is a false sense of security which develops into carelessness. If skill can be relied upon to give safety in the numerous dangerous occupations of man, there is no reason why it should not confidently be applied to designing and working the form of waste weir described above.

CHAPTER XXIV.

WELL IRRIGATION.

WELLS form a very important means of irrigation in India, not on account of their individual capacity, but because of their great number. Unfortunately, there are not recent statistics of them, but the Irrigation Commission of 1903 stated that the then number of permanent wells was 1,669,280 and that they irrigated thirteen million acres ; probably much of this area was double-cropped. In the famine year 1896-97, well irrigation increased by nearly two and a half million acres, while tank irrigation fell by nearly one and a half million acres. In India the average cost of a permanent well varied before the War from Rs. 300 to Rs. 600, according to the size and depth, and a very large one cost as much as Rs. 1,000. The area irrigated by a single well varied from twelve acres in the Punjab to from two to four acres in other parts of India. Ordinary wells are generally worked by single owners, but large ones may be shared by several.

The principal disadvantage of wells is their cost, both in construction and working. The latter has been estimated at not less than three times that of flow irrigation, but in Sind the late Mr. R. B. Joyner, C.I.E., after numerous detailed investigations taking properly into account the value of the labour of men and animals employed, found that the actual relative cost was much greater. In the Coimbatore district, Madras Presidency, where wells average from 35 to 40 feet in depth, the cost of irrigation by cattle power was estimated, from experiments made before the War, at Rs. 70 per acre per annum ; this must be fully five times the flow rate. The great cost of raising water makes lift irrigators most economical of supply. Another disadvantage is that the water from wells, being practically pure, does not fertilise the land which has therefore to be heavily manured. The advantages of well irrigation are, however, many, and greatly counterbalance its disadvantages. First, it is under the owner's sole control and he can thus utilise his supply at his own discretion and independently of canal officials. Then it renders possible of irrigation isolated areas which cannot be commanded by a canal. It makes available water which would otherwise pass away underground unutilised, and by lowering the subsoil water assists in the drainage of irrigated land which without it might become waterlogged. It may tide through a season of drought if the supply from the percolation of the rain which fell in the previous year then continues, as it often does. It may supplement canals which run dry in the hot weather, and thus enable perennial and hot weather crops to be grown under them. It leads to great economy in water, as practically there is no loss in transit to the irrigated area ; such loss was found on the Bari Doab Canal to amount to in the canals to 26 per cent. and in the field channels to 21 per cent. of the whole supply. In the cold weather it furnishes water which is warmer than that from surface sources and is then preferred to that. Lastly, it is adapted to intensive irrigation of valuable produce, and enables two or three crops to be grown annually on the same area. For these reasons the extension of well irrigation is most desirable and can be aided by the State, without final public expenditure, by properly secured advances to the cultivator for construction.

Wells may either be artesian or surface. The former being very expensive to construct, will not be sunk by ordinary irrigators and are therefore not dealt with here. The latter may be classified as "non-alluvial" and "alluvial," according to the nature of the area in which they are excavated. Non-alluvial wells may be in porous soils or fissured rock, and they may be deepened by further excavation, or by having bore holes drilled in their bases, or may be made more effective by driving horizontal adits at their bases. In the dolomite area of the Transvaal charges of dynamite have been exploded at the bases of the bore holes to open out the fissures of the rock. By each of these arrangements the "infiltration cone," which is the subterranean area feeding the well, is increased and more water is obtained, while the supply may be prolonged. To determine the probable amount of that supply it would be best to have the area examined geologically, but, where there are existing wells in it, sufficient information can generally be obtained from them. The subsoil catchment may not coincide with the surface one, but usually will have some relation to it. The best sites of wells are at the bottom of depressions, or on the borders of streams, or even watercourses, as there the surface saturation by rainfall will be at a maximum. Fissured or porous soils will give the greatest and most prolonged amount of supply, As a well is not continuously drawn upon, it should be made of fairly large diameter so as to gain space for storage when it is not in use. Non-alluvial wells can be made permanent if in soft soil by steining ; in rocky soil they do not require this protection. A great advantage of them is that the particles of the strata will not be moved by the inflow to the wells, and even if sand is met with, its admission can generally be easily controlled. Thus the abstraction of the water will not affect the permanence of the well. The difficulty to be met with in such wells is connected with the sufficiency and duration of supply.

Alluvial wells are those sunk in sandy water-bearing strata. Their construction and maintenance may cause difficulties, but, on the other hand, their supply being obtained from a large infiltration cone is generally abundant and prolonged, especially if it is furnished by beds of coarse sand, which may produce ten times as much as ones of fine sand. Moreover, the finer the sand the more trouble it may give by being drawn with the water into the well, thus choking or undermining it. Various devices have been tried to remedy this difficulty. The well ring has been built partly dry, but the sand may fill the interstices of the masonry and pack them watertight, or pass through them and choke the well. The bed of the well has been heavily ballasted to act as a " reversed filter," *i.e.*, with large particles at the top and progressively smaller ones at the bottom, which thus prevents the rise of the sand. Abyssinian tube wells with metallic strainers yield too little for irrigation, for which at least 1,500 gallons an hour (one-fifteenth cubic foot per second) is necessary. Convoluted tube wells of considerably larger diameter have been successful in the Punjab, but not in the United Provinces where the sand is much finer. Wells with masonry or iron rings pierced with weep holes have been suggested; also hexagonal wells of iron or wood with louvres on each face, which are intended to admit water and to exclude sand. An Ashford tube well four inches in diameter and forty feet deep delivered 0.33 cubic foot per second, and one of ten inches, 1.8 cubic feet per second ; at Amritsar a delivery of 2 cubic feet per second is aimed at : the installation there is the most recent and elaborate one in India. The principal novelty in its design is the strainer of the supply tube which is formed of vertical trapezoidal bars radiating in plan and wound over by copper wire under tension, leaving spaces varying with the class of sand met with, which has grains from one eightieth to one hundredth of an inch in diameter. The supply to tube wells is due to the " infiltration head " which results from the difference of water level between the external natural water-table and that in the tube when lowered by pumping : at Amritsar this head is usually about fourteen feet.

A peculiar form is the " *mota* " (see p. 14) well of the United Provinces. This is sunk as an ordinary well carried by a wooden curb a little into a bed of hard clay, or *mota*, and the lower part of that layer is pierced by a pipe extending to the surface of an underlying stratum of sand which furnishes the supply of water. The most favourable condition is when the *mota* exists as a lenticular mass surrounded by water-bearing sand. When water is first pumped out of the well it carries with it some of the underlying sand, so as to form a cavity, or crater, in which water collects, and that is then forced up into the well by the infiltration head produced by its abstraction from the well. If the rate of this abstraction is moderate, the crater remains of small diameter and the *mota* clay roof is able to support itself and the well. When, however, the water is drawn off very rapidly, the greater infiltration velocity thus produced increases the cavity so much that the super-incumbent mass and the well may fall in.

The principle of the formation of craters cannot be taken advantage of in tube wells as the apertures for the admission of water into them are on their vertical sides, and the sand has therefore the tendency to pack close to these, or if the apertures are too large, to enter the tubes. Effect is, however, given to it by a now suggested modification of the *mota* well, described below, which is called the " pipe adit " well. As before, a sand-tight masonry well on a curb will be constructed but will be sunk through the overlying clay and a few feet into the underlying sand. Its base will be formed as a reversed filter, and this will be covered by a cement concrete floor, so that the well will be both water-tight and sand-tight. A little above this floor radial cast iron pipes, say of four or six inches diameter, will be inserted in holes pierced in the masonry ring to receive them. Each of these pipes will end with an auger point and one turn of a helical screw blade to enable it to be forced say, ten feet or more, into the water-bearing sand, and at a small vertical inclination to increase its discharging power. The pipe will be bored at, say, one foot intervals along its base with small holes, say, of half or three-quarter inch diameter, to admit water from the sand. Probably below each hole in this horizontal pipe a crater will be formed in the sand, thus stopping its inflow. If the sand is very fine, each hole may have a small disc cover concentric with the pipe and fixed to it so as to leave clear an annular inlet space, say one-sixteenth of an inch or less wide, which will greatly reduce the inlet velocity. The junction of the pipe with the masonry ring of the well will finally be formed by a good staunching ring flange which will be set in cement mortar so as to be sand-tight. The flow to the well will thus be confined to the discharge in the pipes and that will be admitted to them at such a slow velocity that sand will not be drawn in. By this arrangement it should be practicable to make the base of the infiltration cone several times the diameter of the masonry well at not great cost. As this design does not depend upon the support of the *mota* stratum, it can be applied to any ordinary water-bearing sand formation. Moreover, as the well is founded below the collecting pipes it cannot be undermined by the abstraction of sand carried into these. Where additional supply is required it may be obtained by inserting other rings of pipes at vertical intervals, and they will thus act as elongated weep holes. Should it be feared that the inflow of sand into the pipes will undermine them and make them sink, this can be prevented by covering by discs the holes for two or three feet from the auger points, and for one foot at each end of the different pipe lengths, so that the underlying sand will not be disturbed there and will thus give support. It is hoped that a practical trial will be made of this design, for if it is successful, as seems likely, it should lead to a large extension of irrigation from water-bearing alluvial areas.

CHAPTER XXV.

IRRIGATION PLANTATIONS.

THE large operations of forestry will naturally be entrusted to a Forest Department to carry out, but irrigation engineers are interested in them, particularly when they deal with the catchment areas of their works. Formerly it was thought that forests by themselves produced rainfall, but that idea is not now generally held, as it is considered precipitation takes place from currents of air supersaturated by moisture, derived from the evaporation of immense ocean areas. Forests, however, greatly benefit irrigation in the following respects. First, they tend to attract and precipitate rain which might pass over the area if that were not covered by trees : in this way the afforestation of large catchment areas may increase their yield of water, and thus aid the replenishment of reservoirs. Next, they lessen direct evaporation from the surface of the ground and thus may reduce its total amount, although they themselves lead to indirect evaporation from the subsoil by their leaves. The leaves, however, when fallen and decayed, produce humus, which absorbs violent storms of rainfall, and thereby the saturation of the ground and the fair-weather flow of streams are prolonged. Hence forests tend to lessen the intensity of storm discharge, and so reduce storm-flow and the amount of silt borne down, and maintain the original depth of absorbent soil on the surface of the ground : the diminution of silt is of the greatest importance to irrigation works. The engineer, although working on a much smaller scale, can also obtain benefit from tree growth by thus protecting from erosion the margins of reservoirs and streams, by obtaining timber supplies close to his works, and by adding to food supply. On his canals plantations will improve their scenic beauty and give grateful shade, and they may act as wind breaks to the crops in rear of them. They will produce revenue from fruit and minor produce, the value of which will offset some of the charge for the general establishment. They will afford a test of how the canal staff carry out their duties, for plantations will not thrive if looked after only casually, but require constant care, and while that is being given to them, the ordinary canal maintenance will also receive greater attention. Conversely, when such maintenance is not immediately required, but establishment has to be engaged to provide for possible urgent contingencies, it can be employed on plantation work. Whenever practicable, the engineer should consult a forestry expert, but even if he is unable to do this, it should not be difficult for him to establish and maintain plantations on his works.

In order to conduct plantation work systematically, it is advisable to make out in advance a comprehensive estimate of it for each work, or section of a work, and annually to obtain allotments from the general sanctioned amount in order to finance the operations contemplated during the year. This procedure should result in the ascertainment of the estimated and actual cost of the plantation work; its execution methodically and thus economically; and a proper control of expenditure, annual and final.

Trees in irrigation limits may be classed thus according to the objects they serve—shade, timber and revenue. Shade trees are those planted near irrigation buildings to give protection from the sun or to form camping grounds—umbrageous varieties are desirable for these purposes. Timber trees are those which furnish wood for constructional requirements or fuel. They may usefully be grown on the margins of reservoirs to lessen soil erosion; for such plantations uncultivated land may be acquired to some extent and thus utilised. Waste lands commanded by irrigation channels, or on the borders of streams, can similarly be planted. Near inundation embankments belts of trees will furnish material for emergent breach repairs; it has been proposed, by chaining together the riverside lines of such belts, to form barriers to river erosion. On the canals themselves timber trees may be sown in advance of the more regular avenues in order to occupy the land, and get value early from it. Revenue trees are those that produce fruit, seeds, etc., and thus give a return annually and have not to be felled to realise profit. They are thus the most remunerative of all three classes, and irrigation affords the best opportunity of cultivating the most valuable varieties, such as grafted mangoes. They should be planted along canals and below dams as permanent plantations, and there they can most easily be watched and watered.

The varieties of trees to be planted are those which will flourish best in the local soil and climate, as evidenced by existing trees. M. Contejean's investigations show that salt and lime are by far the most important soil ingredients in regard to the distribution of plants, and their absence, or presence, practically determines that of plants in a given area. This limitation to existing trees should however, not prevent experiments being made with other kinds, which, if successful, will prove of utility : before undertaking such experiments expert advice should be sought as to the probability of success. Along river embankments and near canal masonry works, trees with wide spreading roots should not be planted as they may induce leakage at the first and injure the structures of the second. Such trees will be of most use in protecting stream banks from erosion. On compact areas it is advisable to plant the same kind of tree throughout, so as to facilitate the management of the plantation. On canal avenues, on the other hand, diversity should be aimed at to prevent monotony of appearance due to long lengths of similar plantation. Care should be taken not to plant shallow-rooted trees, which may be blown down, nor those specially liable to decay. Small trees, or bushes, even although fruit-producing, should not be grown on canals, as they will spoil the general effect of the avenue, but may be established near buildings and camps.

The proper final spacing of trees depends upon the spread of their branches, so that the trees may attain full growth and density but not be interfered with by their neighbours. As even in the tropics trees develop slowly, this final spacing, if adopted originally, will then be thin and look badly ; it will, therefore, be better at the start to reduce it by half, and as the trees develop sufficiently, to remove the alternate ones. Along river embankments the plantation lines should not be within ten feet from the river toe, nor within twenty feet of the inland toe, so that the roots may not penetrate much under the banks and cause leakage channels when they themselves decay, or when they are moved by the shaking of the trees during storms. Along new canals trees should, as a rule, not be planted if the acquired land is less than twenty feet wide on each side, unless the neighbouring land-owners do not object to the plantation, or welcome it as a wind-break. They should not be set out within ten feet of the edge of the canals, so that their roots may not enter and block its water-way, nor on the canal side of the inspection path so as to hide the view therefrom. Where the two lines of an avenue are close to each other, and thus the branches might interfere with each other, the trees on each side may be spared midway between those on the other one : where these lines are far apart, the trees should be grown opposite to each other. They should never be planted within thirty feet of a masonry work, so that their roots may not injure it or form leakage lines near it. On old established plantations, where no harm is being done by trees which have been grown at less spacing than that just noted, they need not be removed, and blanks in such avenues can be filled along their original lines.

On wide areas the seeds of trees should be sown *in situ*, but for narrow avenues they should be grown in pots, etc., in nurseries, where they should be reared until about three feet high, and then should be planted out. Watering will be required until the roots of the seedlings have reached the level of permanent moisture in the the soil, and when this has been attained, it should be discontinued after the next monsoon has set in properly. Watering is generally a great expense in starting tree avenues, but should be at a minimum along canals. To reduce the time while it is necessary, the growth of the seedlings should somewhat be accelerated by planting the more valuable varieties in tree holes filled with selected earth, and, if possible, manure should be applied. Large plantations should be protected by continuous hedging along their boundaries ; avenue trees will each require a separate fence. The young seedlings in the avenues should be carefully maintained so that they may develop properly : those in the wide plantations should be thinned as required.

CHAPTER XXVI.

FOUNDATIONS.

THE foundations of engineering works may be considered to be their most important part, for on them the stability of the whole superstructure depends. In irrigation works it is also necessary to ensure that the foundations will perfectly withstand the action of water on them. After the completion of the works any repairs necessary to their foundations can be carried out only with difficulty: in some cases it is practically impossible to effect them satisfactorily. Every precaution should therefore be taken in the initial construction to ensure soundness; that will, moreover, then be obtained at the cheapest rate. On account of the depth at which the most reliable strata sometimes exist, it is not practicable always to found the works on them, and then these have to be seated on less trustworthy formations, and may require modification of their bases to render them quite stable. In order to determine what sub-foundation conditions exist in such cases, so that required modifications of the design may be made, it is necessary to sink trial pits well below the proposed bed level, and, if possible, down to rock.

The natural foundations, on which the structural foundations rest, should be stable, that is, should not move nor spread, and if compressible, should yield only slightly and uniformly, even when wetted, and should not deteriorate. The structural foundations should be designed so as to bear evenly on the natural ones, and not to subject them to pressure which they cannot sustain. Unequal loading is the cause of most cracks in superstructures, and these are particularly dangerous in hydraulic works. The structural foundations should be initially strong enough to carry the superstructure, or should be allowed sufficient time to set, or consolidate, before that is raised on them, so as to obviate undue, or unequal, settlement, and, still more, disintegrating stress. Similarly, each vertical stage of the superstructure should set, or consolidate, before an upper one is constructed on it.

In works intended to store water, leakage should be prevented, as it will cause loss of supply, and, possibly, dangerous deterioration of the foundations. Large vertical fissures should be opened out and filled with masonry laid in cement, or with fine cement concrete; small ones should be grouted with cement under pressure. Horizontal fissures should be cut through by key trenches, which should be carried well below them into sound material, and should be filled with fine cement concrete. Springs occur in many foundations, especially in alluvial formations, where, if the bed is free from them, they probably exist lower down and should be disclosed by further excavation and dealt with. If a spring is not securely sealed, it may break through elsewhere and give trouble in construction, or cause danger to the work when completed. Each spring must therefore be carefully located and treated separately. Subaqueous foundations are the most difficult ones, and are best constructed by surrounding the working area by a cofferdam and keeping the enclosed space dry by pumping. When foundations have to be executed below water level, the lowest part of the construction should first be laid, and the work raised uniformly in sections, over which the water met with should be passed alternately. This will reduce to a minimum the pressure of the water at any point during building.

Masonry dams should have the best of foundations, such as are afforded by dense, solid, hard, insoluble and unfissured rock. The surface of the bed should be tested by striking it forcibly with a heavy sledge hammer, and all shaken parts should be removed. Smooth rock should be roughened generally in order that it may key with the superstructure, and to aid this longitudinal key trenches should be excavated in it. At the toes the rock should be sloped downwards to the centre line; if the central part has a natural slope, it should be cut in horizontal steps to secure proper bedding. Some rock formations are, however, traversed by joints and fissures, although otherwise hard and strong. In such cases the foundation should be considerably deepened, in proportion to the pressure head of the storage and the nature of the strata, and widened to the full width due to the increased height of the dam. The excavation should be completely filled by the masonry, which will thus be in solid connection with its bed and sides, and therefore the dam can neither slide nor overturn, and its increased weight will more than counterbalance any small uplift due to the infiltration of water below the foundations. Where the joints and fissures are not very numerous, a cheaper treatment will suffice. That will consist in excavating a deep longitudinal cut-off trench just outside the upstream toe, and filling it with good cement concrete after the main dam has attained final settlement. The trench and dam will be connected by cement pavement which might be overlaid with a puddle cover. On the downstream side of the dam a narrower, shallower, longitudinal trench will be excavated and filled with drystone, which will form a drain to lead away, harmlessly and without uplifting action, any infiltration water that passes the upstream trench (see p. 58).

Earthen dams are also best founded on rock foundations which should be treated as described above: where the rock is fissured, but is otherwise sound, it may be allowed to remain as it is on the downstream side for drainage purposes. Such dams have the advantage over masonry ones that less perfect foundations of earth will suffice for them owing to the flexibility of the superstructure. The more compact and watertight are the soils, the more reliable will they be. It is best to drain even the most watertight soils, and, if the material will soften when wetted, it is most advisable to do this. Soils which are highly compressible, like peat, those which are powdery or sandy and thus porous, and those which soften greatly when moistened, or are charged with deliquescent salts, should be rejected as foundations, but if they exist only to a shallow depth may be removed and the sites utilised if the subsoils are good. On the upstream side of the centre line of the dam its base should be cut into a series of shallow furrows with gently sloping sides and having small trenches cut in their troughs, which should be filled with watertight soil well consolidated. On the downstream side should be similar furrows and trenches, but the latter should be filled with drystone to act as drains, and should be connected at intervals by cross drains with longitudinal outer drains so as to pass off any water infiltrating into the dam from the reservoir or from rainfall (pp. 59, 79). This formation, beside improving the subsoil drainage, will produce a series of slopes tilted downwards to the centre line of the dam, which will make its earthwork tend to settle inwards, and not outwards, and will thus help to prevent slips. To cut off leakage from the reservoir a puddle trench is excavated, usually on the centre line of the dam. In good compact soils its depth may, as a general rule, be limited to half that of the pressure head of the reservoir at the point considered, and, in less compact ones, to that pressure head. The puddle trench should be of some width, partly to allow of proper consolidation, and, partly, the better to resist percolation which occurs chiefly near the surface. To prevent the puddle and the downstream base of the dam from being softened by infiltration, it is advisable to drain the bottom of the trench.

Masonry weirs on rock foundations should have these treated on a smaller scale like those of masonry dams, but on one sufficient to withstand the pounding action of the overfall of the water: when that is twenty feet or over in height, the base of the weir should be protected by the construction of a watercushion, unless the natural tail level of the stream is deep enough to act as a sufficient protection. Weirs across alluvial rivers generally consist of flat slopes of masonry, or drystone, designed of such cross-sectional length that there is little subsoil flow below them. Their crests are usually formed by masonry walls carried on wells. Infiltration is reduced by impervious aprons and wooden sheeting piles on the upstream side, and erosion is guarded against by tail walls and concrete blocks at the downstream toe.

Cross-drainage works may be subjected to a considerable amount of scour, especially at the ends of their abutments and piers. Their foundations, when not on rock, should, therefore, be carried some depth below the bed of the stream, and if that is erodible, should be protected both upstream and downstream by curtain walls, which will equalise the flow of the whole waterway, and by aprons, and, if necessary, toe walls downstream, to pass that off uniformly from the works and prevent irregular scour. The wing walls can have their foundations stepped up the more they are retired from the current. Alluvial works may require very deep foundations, partly to resist scour, and, partly, to gain support by the frictional skin resistance of their sides. Other such works on good soil have shallow foundations and are enabled to obviate scour by the construction either of inverts, or of long pavements which practically prevent the flow of subsoil water under them. Where the foundations are deep and spring water is met, the substructure generally consists of hollow wells, or of blocks of brickwork carried on wooden curbs, sunk deep enough to bear the superstructure safely. These wells, etc., usually have the interior of their bases closed by concrete plugs over which sand is filled in to within two feet from the surface, which is finished off with concrete, slabbed over to form the foundation of the superstructure.

Retaining walls are liable to fail, not from the weakness of their sections, but from defective foundations which are unable to resist the unequal pressures transmitted to them. Soils which become soft when wetted are unsuitable for such foundations; retaining walls should therefore be founded on those which are incompressible, or nearly so, when saturated. The foundations should be widened by projecting their courses well beyond the front face of the wall: this will distribute the pressure on to a large base, and more equally on it, by bringing the centre of resistance nearer to the middle of the base than it is in the body of the wall.

An ordinary foundation is best constructed of concrete, as that fills the excavation trench completely, is monolithic and free from leakage joints, and is, moreover, cheap and can be constructed by unskilled labour. Lime concrete is sufficient for dry foundations, but for ones subject to water infiltration, the lime should be mixed with a little cement: in bad cases pure cement mortar will be required. The concrete should be carefully lowered into the trench to retain uniformity of mixture, and should be formed in thin level layers, laid one on top of the other to make a course, and each of the layers should be well consolidated. Where the natural foundation is hard and only requires protection, that may be given by limiting the concrete as a strip on the outer side, and, if necessary, facing it with masonry. Concrete foundations, should, as a rule, not be less than eighteen inches thick, and they should not be stepped up too rapidly, so as not to crack under the weight of the superstructure which they should safely carry.

CHAPTER XXVII.

STAUNCHING WORKS.

WHEN water meets permeable soil it tends to descend through it, or to pass along it, until its passage is retarded by some obstruction. After this occurs, the subsoil flow heads up and may thus gain sufficient pressure to continue its course until that is again arrested, and thus its travel continues until it is finally stopped. The initial rate of flow depends upon the pressure of the water at the source of supply, and the further rate on the porosity of the soil and length of passage which induce friction and thus diminish the effective head producing prolonged flow. All ordinary soils are more or less porous ; the greater the porosity the less the resistance to the travel of the water, both in regard to velocity and length of subsoil course. Eventually in most compact soils a distance will be reached where the rate, pressure and amount of the subsoil flow will all be practically negligible. Where, however, a leakage plane occurs, there will be little diminution in these respects, as thus the water will have a defined underground channel, and being but slightly retarded by friction, will pursue its way somewhat as it would do in an open, aboveground channel. It is the object of staunching works to interpose resistance to underground flow (especially along leakage planes), and to make that as short as possible, and so small that its amount and pressure will not be able to cause damage or sensible loss of supply.

Clear water will be the most difficult to deal with, as it does not decrease the porosity of the strata in its passage through them, but, on the contrary, if these are soluble, will increase it, as happens in the dolomite formation. Fortunately most of the waters which the engineer utilises for irrigation are more or less turbid, and thus Nature assists him by causing the inflow to choke the pores of the subsoils and thus to improve their resistance to flow.

This natural staunching will be accelerated by efficient works designed to stop underground discharge. If, however, under natural conditions, or by defective engineering, the subsoil flow is concentrated along a defined line, or plane, it may be able to outflank the works intended to stop it, and may thus lead to a dangerous leak which may destroy the structures meant to be protected. Such concentration of flow is likely to take place at the junction of masonry with earthwork, especially when the latter is green, or newly formed. Not only is the made soil then in its most porous condition, but it will probably settle, and while it is settling, a leakage passage may be formed at the junction. To assist in preventing this the face of the wall abutting on the earthwork should be built with a small batter, and the foundation trench for the structure excavated with small side slopes, so that, as settlement occurs, the earth filling will tend to compress watertight against the masonry and to remain tight against it after the final settlement has been attained. To reduce the infiltration the earthwork should be clayey and free from everything that will cause it to leak, and should be well consolidated, and the staunching masonry should be some distance from the source of water supply. After any water has passed beyond the staunching works, it should be drained off to prevent it from soddening the earthwork downstream. These works should extend at least to full-supply level, and better, to high-flood level, if that is likely to be maintained for some time: if capillarity of the soil will induce percolation to ascend to a still higher level, the staunching works should be raised to cut it off. These being the general conditions of subsoil flow, the way in which the engineer deals with them on certain classes of work will be described shortly.

Staunching walls are walls projecting from the main work, and are best constructed at right angles to that, as it is said " water abhors a right angle "—that is, because this abrupt change, inducing heading up, most increases the frictional resistance to flow. A staunching wall should generally be set out in the centre line of the embankment so as to obtain the greatest amount of earth cover. It should be as long as practicable in order to increase the length of, and resistance to, flow of the creeping water, and its projection into the bank should be in proportion to the amount of water pressure to be withstood. The largest staunching walls will be required for the abutments of an outlet headwall, formed at the centre line of an earthen dam, for the maximum pressure on their foundations will be that due to the high-flood level of the reservoir. As such a staunching wall leaves the headwall, its top may be sloped down, for the pressure on the earthwork above it will be reduced by the length of travel of the water alongside it. Along the upstream face of such a long wall it may be desirable to construct one to three branch staunches projecting at right angles from it, and between them to form smooth vertical joggles in the main wall to increase the bond of the earth with it. Along the downstream face of the wall should be a drystone drain, to lead out of the embankment safely any water which has not been intercepted by the staunch. Low staunching walls (twelve feet and under in height) should have their batters built as rough faces to bond them with the embankment : high walls should have smooth batters, so that the considerable amount of settlement of the earthwork in which they are embedded will not lead to any parting from the walls. The side batters of low walls may be at 1 in 8, and diminish for higher ones up to a minimum of 1 in 18 : the end batters may be at double these slopes. The tops of walls extending up to high-flood level need not exceed two feet in thickness, and should be rounded off to prevent the embankment above from lodging on them, and thus parting from the adjacent earthwork when that settles.

Staunching forks are walls built from the wings of cross-drainage works, and preferably, along the centre line of the embankment to secure good earth cover : they should be raised at least to a foot above canal full-supply level, and should have batters as just described. In compact non-alluvial soils their top projection into the bank may be from four to six feet ; in pervious alluvial soils, it should be double this, or more, according to the porosity of the soil.

Staunching rings are constructed for earthen dam outlet culverts and for cross-drainage culverts. For the former two or more rings may be necessary as required by the length of the work. The one most upstream should be built where much infiltration from the reservoir will not pass above it : the main ring should be at the centre line of the dam, and intermediate rings between these two. The projection into the earthwork of the small rings should be about two feet upstream to three feet downstream, while that of the main ring should be about four feet, the variation being intended to cut off a defined line of flow. They should entirely surround the culvert, their foundations should be carried from one to two feet below that of the invert, and their batters be as noted before. Downstream of the main ring unintercepted water should be drained out of the dam with a free outfall by means of a drystone casing surrounding the culvert.

Cross-drainage culverts in non-alluvial soils may have staunching rings similar to the above and these should be built at the centre lines of the canal embankments when necessary. For culverts in alluvial soil a much greater horizontal projection is desirable, on account of the porosity of the soil, and particularly for sluices in river flood embankments, which are dry for most of the year and will be suddenly wetted by the rise of the floods ; they will thus resemble staunching walls as previously described. The difference in action between a staunching wall, projecting horizontally into a made embankment, and a curtain wall, descending vertically into natural ground, is that the former as its length is increased, does not penetrate into denser earth, as the latter, when deepened, generally does, and hence is not so effective per unit of length in stopping creep.

Core and curtain walls are intended to stop, or retard, flow along the base of a work by projecting from its ordinary foundation into the subsoil. The first are those formed along the interior part of the foundation bed, and the second, those located at, or outside, its ends. If the subsoils are more compact than the surface ones, the water passing beyond these walls will have to descend along their upstream faces and to re-ascend along their downstream ones : thus its flow will be increased in length and will be retarded by the additional friction which is thus caused. If, however, the subsoils are more pervious than the upper ones, this action will not take place, as the water will pass in preference through the lower strata, seeing they give it the easiest course. In such cases the chief advantages of these walls are that they tend to cut off defined leakage planes, and virtually to diminish the volume of subsoil through which percolation takes place.

Dams should have core walls to stop creep along the foundation line and to key them with the bed. Earthen dams are improved by having their foundation surface dressed into furrows (see p. 107). They have puddle trenches under them to cut off subsoil flow. In English practice puddle walls are constructed of superior, water-tight material and extend from the puddle trenches nearly to the tops of the dams : these are not generally formed in India, where reliance is placed on the water-tightness, homogenity and consolidation of the embankment as a whole. When an earthen dam crosses the stream bed on rock foundations, it is advisable to construct there a " central wall," which is really an enlarged core wall. As the top of this will be of some width, it should be formed with a key recess to unite it thoroughly with the earthwork and prevent creep at the junction. Where leakage is likely to take place under a masonry dam, it should be stopped by a cut-off wall constructed along and just upstream of its upstream toe.

River flood embankments should have key trenches (small puddle trenches) excavated on their centre lines, especially where the ground is porous or traversed by fissures. If the bank is of permeable material, a sand core, say five feet thick, should be constructed from the bed of the key trench at least to one foot above high-flood level to prevent percolation in leakage planes through the earthwork. Where there is an abrupt change in the ground level, or embankment top under construction, one or more slip trenches should be excavated to form junction dowels to prevent creep.

Weirs on alluvial rivers should have watertight aprons laid upstream to reduce percolation and thus to lower the hydraulic gradient below them. The silt from the river, which penetrates drystone weirs, improves their stability and water-tightness, and this process can be accelerated by throwing earth into the river upstream. For such weirs small core walls are formed below the facing of the downstream apron to cut off defined flow there.

Canals should have puddle trenches formed at leaky places (see p. 62). Where they pass through porous soil, linings may be laid, or staunchness increased by natural or artificial silting. Cross-drainage works, when necessary, should be made staunch by puddle or cement.

CHAPTER XXVIII.

SLUICES.

SLUICES may be required for one or other of several purposes—for regulating supply ; for lowering the water level in reservoirs, weir backwaters and canals ; for discharging silt from such works ; and for inducing direct flow to a head regulator, etc.

The action of a sluice in dealing with silt is misunderstood, when it is erroneously credited with the power of removing deposited material for a considerable length upstream of it. This, however, it is not capable of doing, for, when it is wholly submerged, water approaches it, not as a defined current with large transporting power, but in a fan-like direction. The cross-sectional area of the inflowing water at a short distance upstream is thus much greater than that of the sluice, hence there its velocity is very small and its silt-moving power is practically negligible. If the sluice is not wholly submerged, the approach flow a little upstream of it is somewhat greater in velocity, compared with the first case, as its area is less, but even thus is not sufficient to scour away silt for any considerable distance upstream. Therefore a sluice is ordinarily unable to maintain, free from silt, a channel upstream of it with a cross-sectional area much greater than its own. To assist it in this respect it is necessary to confine such a channel by means of training walls leading the flow to the sluice : such, for the undersluices of large weirs in Northern India, are known as " divide walls." Owing to the way water approaches a sluice, it is practicable to place two or more sluices comparatively near each other without interfering with their individual discharges.

Downstream of a sluice its action may be very great, as its concentrated discharge, flowing freely, will be maintained for a considerable distance until it is absorbed and neutralised by a large body of quiescent or gently flowing tail water. If that discharge is prolonged in duration and is directed against soft soils, it will scour them away and may endanger the work. To guard against this possible damage, a water cushion should there be constructed downstream of the sluice so as to deaden the flow from it, and to pass it off as a slow-moving current with a large cross-sectional area: this, in effect reproduces, in the reverse way artificially downstream, what takes place naturally upstream.

Such a water cushion, besides protecting the foundations of the work, provides a means of measuring the rate of flow through the sluice, either by treating the cushion as a measuring basin, or by forming in its tail wall a notch over which the depth of discharge can be read and its amount calculated. By making careful experiments, such as those being carried out at the Assuan Dam, Egypt,[1] the co-efficients of discharge of the sluice at different heights of opening can be determined, and these thereafter can be applied to the areas of waterway concerned to arrive at their rates and volumes of discharge. As the water in the water cushion will be in turbulent flow, it will be desirable to ascertain its true average surface level in a small measuring chamber, placed in communication with the water cushion by means of a small pipe, and having a sloped gauge which will give accurate readings by its large graduations. It is most desirable that similar experiments should be carried out at suitable works in India.

Undersluices in a dam have thus practically no direct effect in moving the silt deposited on the reservoir bed: their utility depends upon the fact that muddy water cannot silt above its own surface level. If these sluices are kept open during the early part of the flood season, when most of the silt passes into the reservoir, its basin will be maintained at a low level, and with a small storage capacity, so that both the floods and much of their suspended silt will be carried through the dam, and the silt deposit will be greatly lessened. Such sluices have another most useful property in that by means of them the reservoir surface can be rapidly lowered in case of an accident occurring, or to give the storage flood-absorptive capacity, whereby the waste weir can be greatly aided in flood-disposal, and its length may consequently be decreased, as explained on p. 94. These sluices should have their sills placed a little above the high-flood surface of the tail water, so that that may not reduce their effective discharge. They should be protected by gratings to prevent the entry of logs, rubbish, etc.

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[1] Minutes of Proceedings, Inst. C.E., Paper No 4350, Session 1920-1921, by Sir Murdoch MacDonald, K.C.M.G., C.B., and H. E. Hurst, M.A., B.Sc.

Undersluices in weirs for non-alluvial canals have not to deal with much silt, nor will they lead to dangerous scour of the hard formation on which such works will usually be constructed. They need not therefore be of a large size nor require much tail protection, but should be placed as close as possible to the canal head regulator to preserve a clear channel to it: to increase their discharging capacity their sills should be from one to two feet below canal bed. In weirs for alluvial canals much more silt has to be passed off, and the undersluices are consequently made of considerable size. To prevent their discharge from inducing cross currents, which might endanger the foundations of the weir on alluvial soil, it is necessary to direct the flow to and from them by means of divide walls projecting at right angles from the weir. Further, as their large discharge stirs up bed silt, which might otherwise be carried into the canal, they should be worked alternately with the sluices of the head regulator, *i.e.*, one set should be closed when the other is opened. Not only will the undersluices keep a clear channel to the head regulator, but they will assist the main weir in discharging heavy floods. They will thus permit of the reduction of the length of the weir to what is sufficient for passing off moderate floods, and will thus prevent the formation of silt islands in the backwater, by too slow movement of the river due to a long weir. Their sills are usually placed at canal bed level. Their spans should be sufficient to prevent their being blocked by drift timber. The ultimate development of undersluices is to form the whole weir as an arcade, the vents of which are kept open during the flood season to pass off the then surplus discharge, and are closed by shutters during the fair season to secure canal supply. Such a type of weir is known as a "barrage": it least interferes with the natural régime of the river, and most reduces the deposit of silt and the flood level, but is generally expensive in construction, maintenance and operation.

Head regulator sluices are required to regulate the discharge of the canal and to shut out floods. In alluvial canals they also assist greatly in diminishing the amount of silt that would otherwise pass down them. For this purpose the sills of the sluices are kept, say three feet, above canal bed to shut off bed silt, only clear top-water is admitted to the canal, and the area of the waterway of the sluices is made large to lessen the velocity of entry. If a non-alluvial canal is likely to be enlarged in the future, it is advisable to anticipate this by constructing the sills of the head regulator sluices from six inches to a foot below what would suffice originally. When the time for enlargement comes, the canal initial bed level can thus be lowered to suit its increased discharge.

Along the courses of canals sluices are required to pass off excess supply or to discharge deposited silt. For the first purpose it is desirable that automatic or quick-acting types should be adopted, as the excess may occur rapidly or at night time. For the second one, scouring sluices actuated by hand will suffice: to make them effective they should be located just below where the deposit of silt is considerable, which will generally be in the first three to five miles of the canal. The sluices should open from the bottom upwards to pass off bed silt, and their sills should be from six inches to a foot below canal bed level to increase their discharge.

The types of sluices are numerous. The simplest form consists of horizontal planks, or vertical needles, fixed or removed by hand power alone: an improvement is to substitute wooden shutters or horizontal baulks for them. The next higher form consists of cast iron gates with rustless facings sliding between cast iron grooves: when of small size these gates are each in one piece and are actuated by lifting rods with screwed tops passing through capstan heads bored to receive them and revolved by capstans or hydraulic power. Large gates may also be of cast iron but are generally built up with wrought iron plates: they are usually made in two or three vertical parts, each of which can be raised or lowered independently, generally by means of chains worked by overhead travellers or winches. This subdivision facilitates manipulation but decreases celerity in movement. The best pattern for large gates is the Stoney sluice with bearing rollers mounted in hanging frames, which greatly reduce friction in operation. Then there are automatic gates which open of themselves at high-flood, or any other designed level, and close similarly when the water surface falls below it. Mechanical dams are not much used in India, as the ordinary types are expensive and not easily worked during extreme floods: the best known of these there is the Fouracres' undersluice which acts efficiently. Lastly, there are the shutter crest sluices of large weirs, which are usually hinged at their bases and fall automatically, or are made to fall by quick-acting devices, but have to be raised and fixed by hand, which is a slow process.

The conditions which should be fulfilled by an ordinary sluice are that it should:—be watertight; not liable to jam, either by rusting or by the entanglement of flood-borne *débris*; easy to manipulate; quick in action; and not interfere with the flood waterway. For gates working at great depths, or under great pressure, it would be an improvement to actuate them by hydraulic power, or to reduce the friction of movement by the use of counterpoises. For long shutter crests a cheap and efficient modification of the principle of the drum weir seems desirable. In all cases simplicity of design should be secured, and arrangements made to facilitate inspection and repairs.

CHAPTER XXIX.

PROTECTIVE WORKS.

WHENEVER practicable, irrigation works should be constructed on foundations which are naturally sound, *i.e.*, ones which can carry the superstructure without settlement ; or if compressible, are only slightly and regularly so ; will not be prejudically affected by saturation by water, and will resist its passage through them ; if subjected to erosion, will be able to withstand it ; and will preserve these characteristics unchanged by any adverse conditions to which they may be exposed. Unfortunately, all of these desiderata cannot always be naturally obtained, and then artificial arrangements must be adopted to make the deficiencies good and render the construction perfectly secure. If, however, it is not possible thus to improve the natural state of affairs, risks should not be run, and the work should either be located at another and favourable site, or if this is not available, the idea of carrying out the scheme should be abandoned. Failures of irrigation works may involve extensive losses of life, property and revenue, will lower the prestige of the administration, will lessen the confidence of the irrigators, and may thus retard the growth of irrigation and become a setback to the prosperity of the country. Repairs of such works are always difficult to carry out satisfactorily, and in some cases are impracticable ; even if effected, it is seldom that they will render the structures as sound as they should have been originally built. The construction of ordinary foundations has been dealt with in Chapter XXVI. : what will now be discussed are additional protective works required when inferior formations have to be made secure.

An earthen dam has its water slope protected from wave-wash by pitching : if this is of drystone, as usual, its toe should be carried into the ground, should the surface be hard, and preferably should be formed as a header course not less than eighteen inches deep ; if, however, the soil is soft, the toe should be secured from erosion by wave-lap by covering it with a small mound of insoluble *débris* from the excavations. If the water slope is protected by concrete pitching constructed *in situ*, that should be formed in sections, say, ten feet long horizontally and five feet wide, separated from each other by fine joints, so that the whole covering may follow the dam during its settlement : to prevent these slabs from slipping, it is advisable to embed at intervals in the water slope headers passing through the concrete into the earthwork.

Pitching is constructed on the bed and sides of the canal waterway where the velocity of the flow is increased at aqueducts, etc., to diminish their cross-sectional area, and thus their expense. It is also laid to protect the outer toes of canal banks subjected to wave-lap from flooded areas ; in continuation of wing walls to prevent erosion by flood flow ; and on the sides and beds of cross-drainages and rapids to preserve them. On canal beds the pitching should have a smooth surface, as a rough one would induce vertical eddies which would retard the flow : elsewhere, it should have a rough surface to enable it the better to withstand the action of water and to still that. The pitching should be underlaid with a layer of quarry spauls, etc., eight to twelve inches thick, to prevent wave-lap from undermining it.

If the outlet culvert of an earthen dam cannot be founded near its sill level on a perfectly reliable stratum, it should have its concrete foundations carried deep and spread wide : if there is any doubt of the sufficiency of these precautions, the culvert should, if possible, be built independently of and beyond the dam, but if this cannot be done, the site of the dam should be rejected. A cross-drainage work, especially in an alluvial area, may also require deep foundations, partly to secure these from erosion and partly to gain support by the skin friction of their sides, which thus reduces the pressure on their base. A well-known instance of this treatment is furnished by the Kali Nadi aqueduct on the Ganges Canal, where the springing level of the arches is only twelve feet above river bed, whereas the foundations are carried fifty-two feet below that.

A water cushion is the best form of protection for the foundations of a high overfall weir or of a masonry dam at its undersluices ; it is made by building a subsidiary weir downstream of the main work. If the bed downstream is soft, the crest length of the water cushion wall should not be much less than the bed-width of the tail channel (in ordinary cases it may be seven-eighths of that) so as to lessen the scour. As the downstream bed increases in hardness, so may the crest length be diminished: this will have the good effect of increasing the depth, and hence the protection, of the water cushion. The tail water of the stream, if sufficiently deep for low discharges, may obviate the necessity for a water cushion, seeing that for high discharges it rises more quickly than does the afflux producing it. The depth of the water cushion when the stream bed is of rock, or is protected by good pavement, may be made one quarter of the drop from afflux to tail level, and should be increased when the bed is of softer material. The length of the water cushion in soft soils is usually made equal to twice the square root of the product of the afflux height over the weir multiplied by the depth of drop from the surface of the afflux to that of the tail level; it may be reduced for harder material in the bed. If the main weir is low and boulders are liable to be carried over it, the water cushion should be increased in length and its tail wall replaced by a paved slope, rising, say, two to five to one, so as to allow the boulders to be carried on. Should the main weir be high, boulders are likely to be trapped in its backwater and not to be borne over it. The great advantage of a water cushion is that the force of the water entering it is destroyed by the inter-action of the particles of the water themselves, usually without assistance from structural arrangements, so that the bed is not subjected to much erosion: fully to develop the resistance by such inter-action the volume of water in the cushion must be sufficiently great. Another advantage of the design is that the on-flowing water is passed over the crest of the level tail wall in a comparatively thin sheet, which has small destructive effect on the masonry. As the flow is discharged uniformly to the stream bed below, it thus has its erosive power diminished as much as is practicable. Water cushions are therefore best adapted for dealing with high velocities and long-continued flow, and to sites where the reduction of velocity downstream is of benefit. A stage in the evolution of the water cushion is to make it substantially divide the total overfall, when that is considerable, with the main weir. The ultimate stage is when there is a series of water cushions one below the other, so as to negotiate a very large total drop, *e.g.*, from the waste weir of a deep reservoir to the natural drainage line of the country below.

A paved apron is another form of protection of foundations: it consists of a covering of pitching, or masonry pavement, laid on a slope whereby water is conveyed from a high to a low level and is thus prevented from causing scour. This prevention is effected mainly by the friction produced by the apron, and as that is considerable and will re-act on the structure, it tends to destroy it. Should the apron not be able to resist this action, parts of it will be displaced, or carried away, with the result that the flow over them will be concentrated. Thereby it will have an increased destructive effect, which if repairs cannot at once be carried out, may still further develop until the apron is considerably damaged. The advantage of an apron is that it does not greatly lessen the velocity of the discharge, and thus does not necessitate much increase of its flood waterway. The slope of the apron should be continued to reach beyond the probable limit of scour; and should end at a toe wall founded to some depth, and protected downstream by a substantial talus of boulders, etc., so as effectually to resist scour, which, if it occurred, would undermine the structure. An apron is best adapted for dealing with short-lived and comparatively gentle flows, such as occur at cross-drainage works. It is also suitable and economical for adoption where there is a considerable fall in the country and foundations are bad—it then becomes a "rapid." An apron is the most important part of the "Bell bund," which is constructed to guide large alluvial rivers at the sites of weirs and railway bridges. The long sloped weirs on sand foundations across such rivers may be considered to be the ultimate development of aprons. An invert of a cross-drainage work may be held to be a horizontal apron under it, thus differing from the ordinary sloping apron which is downstream of it. An apron is best made of rough pitching as that effectually breaks up the flow of the water; to lessen the action of the discharge, that flow should not be deep; to make the pitching secure, it should consist of large stones, well laid and packed with spauls and resting on a layer of rock *débris*, etc., to prevent its being undermined by wave-lap. Further, to protect the apron when necessary, as in the case of an alluvial weir, its whole surface should be divided into compartments by longitudinal and cross walls well founded, which will thus prevent much extension of any local displacement that may occur by erosion.

A curtain wall in non-alluvial country is built where the soil is sufficiently hard to resist ordinary surface scour, but is not able to stand concentrated flow. In most channels there are parts softer than the general bed, and those are liable to be scoured away, and thus to form lines of concentrated flow, which are likely to become deeper and wider. By building a level-crested curtain upstream of where such action might otherwise occur, this form of retrogression of levels is prevented, as the discharge of the stream is thus evenly distributed over its bed. Owing to their great width waste weir channels, in all but the hardest rock, are subject to such irregular deep channelling, and then may require this form of protection.

A curtain wall in alluvial country has to deal principally with subsoil, rather than with surface flow. When the soil is of a homogeneous character which increases in imperviousness as it descends, a curtain wall adds to the length of the passage of the subsoil flow by twice its depth, and thus lowers the hydraulic gradient, and thereby diminishes the upward pressure of the water on the parts of the structure downstream of it in proportion to its depth. When this water meets the curtain, it has to descend to the base of the wall to pass it, and then, owing to the greater permeability of the surface soil, rises to travel along that. If, however, the soil is not of a homogeneous nature, but is traversed by fissures or porous planes, the office of the curtain wall is to cut off excessive flow down them. In both cases it virtually reduces the volume of the subsoil percolation below the work, and thus the quantity of subsoil flow, thereby rendering the structure more water-tight.

CHAPTER XXX.

HISTORIES OF WORKS.

THE current work of an engineer is more than sufficient to keep him fully employed, and he may, therefore, not welcome a suggestion to increase it. That suggestion is, however, now made because of its general importance in relation to his charge: also, although it adds a little to the record he has anyhow to keep, it will assist him in managing his works, and may thus reduce his labour elsewhere. By adopting it he will get a more comprehensive view of what should be done, and he will realise he is thereby connecting himself both with the past and the future, and is not merely a temporary holder of his post, to be forgotten soon after he leaves it: all this should give him increased interest in the schemes with which he is connected. The suggestion is that a short history should be maintained of every large project or work, and that each year's progress on, or events connected with, it should be described in a continuous record, all in one place and preferably in book form. It is true this is in one sense effected by annual administration reports, although not consecutively, but in another sense it is not, for those prescribed accounts are usually confined to bare statement of facts and are thus not the most interesting of professional literature. Moreover, administration reports are for general reference, whereas the history will be a guide exclusively for the engineer in charge. The suggested history for a large scheme should have for its main aim the compilation of a narrative which will describe shortly what led to the proposal for the work, give an account of its construction and note all principal engineering events which then happened, and have since occurred year by year; the difficulties in execution met with; the amount of success attending the measures taken to overcome them; and improvements in those methods, or of the original design, which suggested themselves during construction. A separate history should detail all proposals made for benefiting the charge generally;

for instituting new investigations, and for continuing, or modifying, old ones in progress; and should note all schemes contemplated, and give the writer's reasons as to whether they should be prosecuted, postponed, or abandoned. This last is of considerable importance, as occasionally projects are put forward which have previously been enquired into and negatived after full enquiry, all of which in the lapse of time has been forgotten. Conversely, this history will prevent the oblivion of good projects or proposals which, at the time they were made, could not be carried out in the then existing conditions. Lastly, it will record the ideas of different engineers on the same subject, and this variety of opinion should be of great value to their successors, who from local knowledge and from acquaintance with the professional ability of their predecessors, should be able to come to sound conclusions as to what should be carried out or laid aside. In regard to statistical record probably as much as is necessary is already maintained, but even for it, improvements of, additions to, or excisions from, that record may suggest themselves, and the suggestions may be worthy of being registered permanently. The main objection to statistics is that usually they present only the dry bones of the subject: these would be clothed with flesh were they supplemented by observations pointing out the general interpretations of the figured tables and the deductions to be drawn from them. A list of important reports, correspondence, etc., and references to where they are filed would add to the completeness of the history. With these general remarks a few notes will be made as to how effect can be given to the proposal in respect to certain classes of works and schemes: naturally, these remarks are but general suggestions and not all-inclusive prescriptions.

Large projects should be illustrated by fair-sized index plans on which all changes made subsequently to the original construction could be marked and have reference numbers, corresponding to which would be a tabular statement showing where the detailed plans and estimates are recorded. Similarly, the sites of suggested supplementary schemes could be shown. As noted above, the history should give briefly an account of those changes; the results expected from them and actually obtained; the reasons for the differences; and, when necessary, further proposals to secure, or increase, the intended development: also reasons for prosecuting, postponing, or abandoning supplementary proposals.

For storage reservoirs, either with masonry or earthen dams, a narrative should be compiled describing any notable events which have happened ; any damage done ; any reconstruction or additions carried out ; any great variations in storage impounded and the causes thereof ; descriptions of how the storage was expended, and any economy in supply effected ; remarks as to the largest floods, the maximum height which they attained, for how long that was maintained, and the total volume produced ; notes as to the effect of the floods on the waste weir and its tail channel ; and other points of interest. Tabular statements should be prepared showing for each year, in comparison with previous ones—the amount of vertical settlement, or horizontal displacement, of the slopes of the dam ; the progress of silting of the reservoir bed ; the amount of the percolation discharge and the total loss by evaporation and absorption ; also ones of rainfall, reservoir levels and outlet discharges, etc.

For masonry weirs many of the remarks just made apply. The effect of floods on protective works and on the erosion of the river bed downstream ; the working of the various sluices ; the variation of river levels and supply ; and the progress of silting in the backwater are among matters deserving of record.

Large alluvial rivers should be dealt with in detail by a riverain survey, but the proposed history would usefully summarise the results of this. The principal alterations of course ascertained by the survey should be noted with suggested reasons for their occurrence ; forecasts made of their probable effect on the general course of the river, or at certain important works; and proposals put forward for any protective measures considered necessary.

River flood embankments should have maintained for them, furlong by furlong, registers of top level, top width and side slopes ; high-flood level and free-board ; expenditure on ordinary and special repairs ; and erosion statements. The main features of these should be noted in the history, which should in particular record shortly the principal works carried out or proposed, and should be illustrated by a small scale index map showing their location and referring to their detailed plans and estimates. Extensive breaches should be noted on with reasons for their occurrence ; and general remarks made as to the damage done thereby to works and cultivation ; any special features of the repairs executed ; and as to the expenditure incurred on restoration. The effect of new embankments on the régime of the river should be noted.

River reclamation works can be properly carried out only if a careful record is maintained of the operations undertaken and observations made. Gauges should be established to determine the surface gradient at them, and surveys of the river's course and contoured plans of the foreshore should be made. This will show what parts of the reclamation are successful and what are not. The history should summarise the record so that the progressive results may easily be seen. Similar remarks apply to all alluvial river training works, the continued effect of which has to be watched, insured and carefully recorded.

Large alluvial weirs should have shortly described any damage done to them and their protective works ; the cost of repair incurred thereon ; and suggestions for further remedial measures, particularly in respect to training works. The effect of silting in the backwater, with especial reference to the formation, or growth of silt islands therein, should be noted.

Canals should have index plans and narratives prepared as described under projects. An annual leakage statement should be recorded as to the results obtained by staunching measures. There should be a list of the larger subsidiary works with details of their principal dimensions, and, similarly, one of the different canal sections ; also high-flood levels and discharges of cross-drainages. The revenue part of the history should record how irrigation progressed ; the character and effect on the irrigation of the seasons and the supply available ; the kind of crops grown and reasons for their selection ; and the progress of the revenue and the causes affecting it. Tables of areas irrigated, out-turn and value of crops irrigated, gross revenue, working expenses and net revenue should be made. Where practicable, the summary should take the form of diagrams comparing one year with another for a series of years.

CHAPTER XXXI.

PROJECTS.

THE preparation of an irrigation project forms one of the most fascinating duties of an engineer, for while carrying it out he sees in his mind's eye how his efforts may result in the development of the country by taking advantage of its natural assets, and in the consequent increase of the prosperity of the cultivators, which reacts on that of the whole population who will share indirectly therein. He must, however, not let impulsive enthusiasm run away from mature judgment, but must preserve an even balance and regulate his imagination, for a scheme which may tempt by its possibilities may be barred by practical difficulties. A brilliant amateur may get the suggestion of the former, but the expert must be guided by the limitation imposed by the latter. The irrigation engineer cannot do better than learn from the experience of his predecessors ; he should realise the difficulties with which they had to contend, and should appraise fairly the measure of their success or failure in overcoming them, and in making use of their opportunities. Again, he will benefit by studying Nature and seeing how she accomplishes her task—that in detail may be extravagant, as her resources are great, but her general arrangements are in accordance with physical laws which must be studied and complied with, as they cannot successfully be set aside. She frequently gives hints which can usefully be followed and applied to the working out of the problems she sets. The engineer should constantly be observing and noting what schemes are feasible, and should study the reasons, subsequently ascertained, which caused others that originally appeared promising, eventually to prove illusory. Even if nothing definite at first results from such examination, he will by this training improve his eye for the country, and later on may thus be able to put forward a thoroughly satisfactory scheme. He should not despise the day of small things—minor projects may give scope for his ingenuity, and the frequent practice of that may lead to the design of a successful large work.

Naturally one of the first matters the engineer must acquire is a thorough knowledge of the amount of water with which he has to deal in his works, whether those may be connected with storage, flood disposal or distribution. By constant general observation he can make himself acquainted with the possibilities of his charge, so that he can select for further examination those schemes which are likely to be productive of sufficient but not excessive supply, and reject those which will yield too little or too much, and will thus reduce that examination both in cost and time. Such examination consists in the actual determination of the amount of water of which the works have to dispose, and that has to be made by gauging observations of stream discharge and rainfall (p. 52). In this case, as in others, "science is measurement," and general observation, however skilled, must be tested and confirmed by detailed investigation. Usually the engineer will find it best to propose projects which are self-contained and not dependent on others for additional supply. He should endeavour to keep water at the highest level practicable, as thereby he will obtain the largest command with the shortest length of channel, thus reducing loss in transit to the minimum, and by concentrating the irrigated area, will lessen the cost of cultivation and the amount of supervision necessary. Every advantage should be taken of natural flow, chiefly to diminish the cost of any storage works that may be required to supplement it, but also to obtain water of the most fertilising character.

A project should not be started until the whole of the neighbourhood has been examined to ascertain that no better scheme in it is possible: for that reason the engineer has been recommended above to acquaint himself early with the physical conditions of his charge, including its water supply. From a purely engineering point of view the head of a catchment should be dealt with first, and lower projects carried out in the order of their nearness to it. If, however, this cannot be done, the lower schemes should be designed so as not to interfere with the upper ones should they be executed subsequently. If, however, it is feasible, valuable experience will be gained of the sufficiency of the supply available, and of the modifications in design desirable, for the lower works, and effect will be given to the principle just recommended of utilising water at the highest level practicable. A scheme should, if possible, be started on a scale which will suffice only for the probable demands of the near future. That being done, it should be arranged to be expansible, so as to meet the requirements of later years when a larger development of irrigation may take place. Thus the capital expenditure will be increased only in proportion to such development, and not greatly in advance of it, and thus interest charges will be kept as low as possible. Were the opposite course followed, and the project commenced of its final full size, the gross revenue would, at first, give but a small return on the expenditure, and the net revenue a much smaller one as maintenance charges would be increased by the large scale of the works. The conditions most favourable for the success of a scheme are—water must be required and be made available in sufficient quantity; competent cultivators must be numerous; the distributing works must be completed early; the irrigated area must be compact, fertile, level and near good and easily reached markets; the capital and maintenance cost of the works should not be excessive, nor the irrigation rates high, while the net revenue should be fair in amount. Large works should be relatively the cheapest to construct and maintain, and, if successful, the most beneficial to the irrigators and to the country as a whole: if unsuccessful, they will be costly failures and retard the growth of irrigation. Small works will usually be more expensive *pro rata*; if successful they will improve isolated areas which otherwise could not be developed: if unsuccessful, they will not cause much loss or discredit. Medium-sized works will have advantages and disadvantages comparative to their magnitude.

Before a large project is selected for detailed investigation it is necessary that the country in its vicinity should be examined by means of a reconnaissance survey. The objects of this are to obtain, cheaply and quickly, general information as to the nature of the area examined, the facilities offered by it for irrigation, and the relative merits of all projects practicable in it. The reconnaissance will thus enable a plan to be drawn up for the best general development of the tract considered, so that each scheme recommended will work in, and will not clash, with others feasible, and will avoid the mistake of carrying out irrigation in a piecemeal way. To compare those relative merits, approximate surveys of the works and irrigable areas should be undertaken, and rough plans and estimates of the proposed works should be made, more or less on the same general lines, so as to give a fair comparison of the costs, advantages and disadvantages of the competing projects. As soon as a likely scheme has been discovered, all hydrographic investigations should at once be started and continued so as to get as lengthy a record of them as possible. The general results of the reconnaissance and its index plan should then be communicated to all the different departments which should be consulted—revenue, agricultural, survey, forest, public works, geological, etc.—so that they may advise on matters connected with their own operations and report about them. With all such reports before it, the administration will be in a position to determine whether it is, or is not, advisable to examine any scheme, or schemes in greater detail. It will, of course, have to see that the project suits the requirements of the irrigators, and that these are not to be sacrificed to render the scheme remunerative.

After such further examination has been decided on, the irrigation staff should proceed to draw up the selected scheme in complete detail, and submit its plans and estimates with a report, concise but comprehensive, giving the history of the project, the reasons which influenced its selection, its scope and the results anticipated from it. Attached to the report should be all technical statistics, hydrographic tables and revenue forecasts, and the opinions of the other departments recorded in the preliminary enquiry. This final irrigation report may show that the scope and prospects of the scheme, as originally outlined, have been materially altered. If this is the case, these other departments should again be referred to so that they also may give their further opinion. The administration will thus have before it the scheme completely drawn up from the technical point of view, and thoroughly examined by experts of other departments, so that it should be able to decide whether it should or should not be constructed.

This procedure described for large schemes is no doubt lengthy, but if properly carried out will probably result finally in a saving of time, and yet secure proper examination without which costly errors may be committed. For small schemes much less investigation is, of course, sufficient, but so far as it goes, it also should be thorough. While the cause of failure of certain irrigation projects was undue haste in their preparation, an excessive amount of investigation and the reduplication of work by many revisions, or alternative schemes, is prejudicial to proper progress. During the course of many years many matters discussed and previously settled may be forgotten or re-opened by new investigators who may come to conclusions less correct than those of the original ones. Such prolonged investigation is not only costly in itself, but also retards the progress of the country: it disheartens the staff who have to continue it, as they will be doubtful if their proposals will be accepted and lead to actual construction. The recommendation therefore is to obtain early by concentrated effort, and by a staff specially recruited and reserved, a thorough examination of a large scheme from all points of view. The only investigations which should be prolonged are those which deal with hydrographic record, and they may be shortened by starting them as soon as it is seen the scheme will probably be practicable.

CHAPTER XXXII.

DESIGN AND CONSTRUCTION OF SCHEMES.

WHEN designing his schemes the irrigation engineer has first to see that he has provided sufficiently for supply, flood disposal, and irrigation consumption. Next, in respect to the individual works of which they consist, he must arrange that they will be quite safe under the severest conditions which may test them, as any large accident they may sustain may cause much loss to revenue, cultivation and other interests and even to life itself: and may lead to a set-back of irrigation development. Thus a dam must be raised sufficiently above the high-flood level, and not merely above the full-supply level of a reservoir. A waste weir, a reservoir outlet, or a cross-drainage work must be planned so that its discharge will not be interfered with by trees, brushwood, etc, carried down by floods. Where the growth of irrigation may be expected, the different works should be constructed originally so that they may be enlarged subsequently without much sacrifice of what was first built. The designs adopted should follow well-tried examples, with such modifications and improvements as experience may suggest: it is not generally advisable to propose entirely novel and untested designs as they may fail to effect what was desired. As irrigation is a quasi-commercial concern, care has to be taken to keep the capital cost as low as possible by choosing the most economical sites, types of works, and alignments practicable, and by designing massive and permanent, rather than ornamental, structures, which would, anyhow, be out of place in the remote localities where they will chiefly be built. At the same time it is necessary to reduce maintenance cost, as far as may be, by making all provisions required, and desirable to aim at neatness and appearance as well as solidity. Simplicity in design secures appropriateness, and thus a beauty of its own, and avoids many difficulties, but should not be carried to the excess of baldness: needless elaboration may look tawdry and lead to trouble. Designs should permit of the easy inspection, maintenance and repair of works: this is particularly the case for the parts of the structures which are either of a temporary or somewhat intricate character, or both, such as sluices. Lastly, designs should have reference to the size and importance of the works—a small pick-up weir may have an irregular plan, but a large masonry dam should be set out on bold and simple lines.

When constructing his works the engineer has first to attain complete soundness, both of material and execution, especially in those cases where the structures are exposed to the continuous test of water day and night, year after year. Unless construction is absolutely sound, a design, however good, may not prove safe; whereas a poor design, well built, may last, although it may not serve its purpose adequately. Naturally the best results are obtained by the union of excellence both of planning and building. A failure of an ordinary land work may lead only to inconvenience, and that only of some temporary duration, while its repair may not be difficult of execution and may result in completely restoring the efficiency of the structure. Extensive damage to an irrigation work may cause the losses enumerated above, one of which, loss of crops, may more than equal in value in one year the capital cost of the whole scheme. The repair of such a work is generally difficult and is sometimes practically impossible; even if quickly effected, the cultivating season, and thus the crops, may be lost; the reconstruction, if tested at once by water, may not be so good as the original structure, which if it were a combination of earthwork and masonry, started under the most favourable conditions and improved with age. These remarks apply with especial force to foundations, which should be most carefully laid so as to be both sound and watertight. In regard to materials, the quantities required on a large work are so great that they have usually to be obtained locally, or the cost of execution would be much enhanced. This consideration has therefore to be borne in mind when locating the works, but the actual constructor can best show his capacity by making the most of local conditions. Only the soundest materials should be used, as inferior ones will, at least, lead to increased maintenance charges, and may, indeed, entail the cost of early rebuilding.

When once works are started they should be pushed on to completion as rapidly as obtaining soundness in construction permits. Usually the larger and more difficult structures should first be taken in hand so that they may be the earlier finished, and have the most time for self-consolidation, or setting, before they are subjected to water pressure. The smaller works may well be deferred for as long as their size permits, so that the building of both the large and the small ones may be finished at about the same time. The design of the major works will of course have been made in advance in complete detail, but that of the minor ones may not then have been elaborated: this procedure will therefore allow of the experience gained on the former being utilised in improving the type of the latter. Occasionally, however, it may be desirable to defer a part of a scheme which may not be absolutely necessary during the early stages of the growth of irrigation until the expansion of that demands its execution. Care should naturally be taken not to impede that growth by delaying anything required to facilitate it. Thus it would be a mistaken policy to construct a canal and not provide it with distribution works. This was often done in the early days of irrigation when the engineers were more concerned in the success of their major constructions than in that of the humbler minor ones, although the cultivation and the revenue depended directly on the latter. To sum up, these prescriptions are intended to secure the quickest completion of the scheme practicable, or desirable, so as to attain the earliest start of actual irrigation, but not to anticipate sanguinely a rapidity of growth which may not take place. Thus the capital sum at charge will be reduced to the minimum until it can give a return, and will be increased only to keep the works somewhat in advance of the development of irrigation.

During the execution of the works it is not desirable to change the superior members of the staff: they will thus know all about them from start to finish, will continue to gain experience, which should lead to economy and rapidity of execution, and can be held responsible for everything that happens. No one likes to build on another man's foundation, and the layer of the substructure will, more than others, be interested in carrying out the superstructure to successful completion. It is false economy to pare down works during construction only to avoid or reduce an excess, as subsequent alterations will probably cost more than the savings thus effected. The most that should be done in this respect is to omit non-essentials, or sub-works that can be postponed without disadvantage. Nor should the programme be retarded, much less stopped, because of an excess, as this, by the extra cost of re-starting, will involve larger final expenditure, and will delay cultivation and thus will postpone the earning of revenue. The final consideration should be the proper time in which to take construction in hand: when prices are normal this is not of importance, but when labour demands excessive rates and financiers of loans high interest, it will be a matter of ordinary prudence to postpone the execution of large works until ordinary conditions obtain. To start and carry out a project in a period of temporary inflation will naturally prejudice the permanent earning capacity of the scheme during the much longer period when revenue rates will have to be reduced in keeping with the general fall in the cost of living.

CHAPTER XXXIII.

LARGE RESERVOIRS.

WHEN inspecting a site for a dam the following main features should be scrutinized as on them depends its desirability or the reverse. The longitudinal section of a dam gives an indication of its probable cost; the sites available for waste weirs and outlets show whether or not the work is practicable; and the configuration of the reservoir basin determines if the storage will, or will not, be sufficient in amount and what will be its comparative cost. The catchment area must be of sufficient but not excessive size, the reservoir basin retentive, the dam foundations sound, and materials for construction ample and cheap. Careful inspection by an observer who has trained himself so as to get an eye for the country, and a little general survey will usually lead to sound conclusions; according as these are, or are not, satisfactory, the advisability of further detailed examination, or the immediate rejection, of the scheme can ordinarily be decided.

The cross-sectional area of a dam varies greatly with its height; that of an ordinary earthen embankment is roughly two-and-a-half times the square of its height; the proportion for masonry dams is less, but still is considerable. Thus a long, low dam may have a smaller volume than a short, high one, and therefore the former may be cheaper to construct originally, or to raise subsequently, than the latter, and also will be safer. For this reason the most economical site is likely to be one at which there are ridges on both sides running down to the stream to be impounded. For a masonry dam, the sides of the river gorge may be steep, but it is advisable that they should be somewhat similar in slope so that the structure may be subjected to symmetrical pressures. For an earthen dam, the ends of the ridges should have gentle slopes not exceeding two to one, as the earthwork will have a tendency to slip off precipitous ones, especially if its base is likely to be lubricated by the infiltration of water. A ridge not only cheapens a dam but also improves its drainage, which is a matter of importance in the case of an earthen one. The ridge should not be very narrow, for if it is, it may leak, and it may render the construction of the work costly and its subsequent enlargement difficult. Generally a ridge is an indication of hard foundations, but some engineers consider that it points to disturbance, which may have fissured the strata and thus have rendered them pervious and unsound. For this reason particular care is necessary to test a ridge by numerous trial pits, and where there is any reason to suspect its suitability for foundations, to get geological advice on the subject. It is usually not advisable to combine a masonry dam at the gorge with earthen flank embankments, as the junctions of the two will entail difficulty and expense in securing water-tightness, unless they are made where the height of the dam is small. The combination is, however, practicable and economically desirable when on one side of the gorge the ridge rises above reservoir high-flood level and thereafter continues at a lower level which can be blocked by embankment while the gorge itself can be closed by masonry: the two forms of structure will thus be independent of each other. The nature of the foundations is a matter of the utmost importance and has been discussed in Chapter XXVI. Where the strata on the surface are hard, a fair idea of the probable depth of the foundations may be formed by inspection, but where reliable formations are not thus disclosed, examination by trial pits will be necessary, and the preliminary rough estimate of the scheme should provide liberally for this item. Although for ordinary heights both masonry and earthen dams can be constructed with equal safety, for ones exceeding 100 feet the former type is generally preferable: it is also usually more suitable where the rainfall is excessive, for steep river gorges, for defective waste weir sites, and where the slightest risk must not be run, as for a town water supply. Of the two forms earthen dams have ordinarily the advantages of requiring less perfect foundations, and of being cheaper, more quickly executed, more easily raised when necessary, and more suitable for construction by the employment of famine labour.

A waste weir, although desirable, is not essential for a masonry dam, and that may be a great advantage of such a type of structure: where a site for it does not exist, floods may be discharged over a lowered part of the crest of the dam, or through undersluices in it. These flood-flows should preferably be designed at the stream crossing, so that their outfall may be protected by the natural tail depth on the stream bed, or have that increased artificially by a water cushion, in order that the foundations of the dam may not be injured. A waste weir is absolutely necessary for an earthen dam, as on it the safety of the reservoir depends. The best site for it is one separated by natural high ground from the end of the flank of the embankment, which will thus not be affected by erosion by floods. For this reason an inferior site is one at the immediate flank, and the worst one, through the flank with embankment on both sides of it. Both these latter sites will require protective tail works to safeguard the dam and divert the floods away from it. The desiderata for a waste weir are—sufficient length to get proper flood-discharging capacity; a flat longitudinal section, a cross section gently sloping downstream and hard strata to diminish the cost of the works and to increase their security; the proper elevation to obtain the required amount of storage; and a good outfall to lessen the damage by floods. It will be best if in longitudinal section the ground dips on both sides to the centre, as thus there will be a valley down which the tail floods will be directed in a confined channel which will improve itself by scour and erosion. If this natural profile does not exist, an artificial channel can be excavated so as to act similarly. It is sometimes not easy to secure directly the essential of sufficient length for the waste weir when the ground rises steeply at its flank. This difficulty can, however, be surmounted in two ways—by utilising the flood-absorptive capacity of the reservoir (as pointed out on p. 91), or by the device of a tail channel parallel to the waste weir. In this latter design the waste weir wall is set out in the reservoir basin at the flank of the dam nearly parallel to the high-flood contour of the ground, and at a distance from that sufficient for the space required by the tail channel; thus the weir will usually be at an obtuse angle to the dam and not in line with it. The tail channel will vary gradually from a small width at the upstream end of the weir to the full width at its downstream end. As this channel can be excavated with a steep fall, the velocity and depth of its high-flood discharge may be made greater than those over the weir, and thus its maximum width will be considerably less than the length of the weir. If advantage is also taken of flood absorption, this design will be suitable for a naturally very narrow site. An Italian design for a waste weir is to construct it as a siphon coming into action a little below high-flood level. It is claimed that the high-flood discharge takes place through the siphon with only a very small rise in the level of the reservoir, so that the height and the cost of the dam can be considerably reduced. It is believed, however, that the design has not been carried out on a large scale.

The outlet of a masonry dam can be placed where it will most suit the alignment of the canal from it. For an earthen dam consideration must chiefly be paid to the safety of the embankment, for an outlet, although a necessity for an irrigation scheme, may be a source of danger if insecurely founded or badly constructed. The best site for an outlet under such a dam is at a small saddle in its longitudinal section remote from the river crossing, as thus the embankment will settle uniformly on both sides of it and infiltration from it will not pass under much of the earthwork and tend to lubricate its base. Conversely, the worst site is on the steep slope of the river crossing, as there unequal settlement of the dam and lubrication of its base are likely to take place. The best site of all, but one which is generally expensive, is at a saddle beyond the flank of the dam, as then the two works will be independent of each other, a condition which some engineers consider to be essential for safety. Another good site is near the flank of the dam where the water pressure will be small. If there is a cross ridge jutting upstream from the main one on which the dam is raised, it can be utilised for carrying the approach bank to an outlet tower, or headwall, built clear of the dam, and thus both these works will be independent of that. The best type of outlet, and one especially useful for aiding the waste weir in discharging floods, is the headwall on the centre line of the dam, as that is built in the open, like a masonry dam, and large undersluices can be arranged through it. It is unfortunately expensive, but its cost will be least when there is a deep saddle available for its location. The best foundation for an outlet is sound rock, somewhat below the ground surface, as then the culvert can be constructed below the base of the dam and will thus be independent of it. Failing rock, the excavation for the outlet should be carried deep down to a sound stratum which will not deteriorate when wetted, and the foundation should be wide and made of concrete of some thickness to distribute over a large area the weight of the superstructure and carry that safely. The level of the sill of the outlet should be placed so that the storage below it is about one-ninth of that above it. This will provide space for the accumulation of silt, and will raise the command of the canal.

A reservoir basin is most capacious when its cross section is flat, and its water-spread near the dam is wide, as there the depth of the storage will be at a maximum. The greater its mean depth, the less will be the loss from evaporation, but the greater, other things being the same, will be the loss from absorption: to reduce the latter a retentive site should be chosen (p. 63). A generally favourable site for storage is where the dam is situated below the junction of a considerable tributary with the main stream, for there water should be impoundable up two valleys and the water-spread at the junction should be considerable. Such a site may also afford good foundations. As a rule it is better to store the same quantity of water in one, rather than in two or more, reservoirs: thus the cost of storage and maintenance, and the loss from evaporation and absorption should be the least practicable. It is advisable not to have reservoirs "in series," that is, one below another on the same stream, for the failure of an upper one may entail that of the lower ones. Where, however, such a series has to be constructed, it should be arranged to make the storages progressively larger downstream, so that each may be the better able to absorb abnormal floods from those upstream. The capacity of a reservoir should be about 10 per cent. larger than the average yield of its catchment: it will thus fill, or nearly fill, in all ordinary years, and will not be excessively large in moderately bad ones. The amount of storage required depends upon the duty, or rate of consumption, the extent of irrigable area, and on losses by evaporation and absorption and in transit. The culturable area in a reservoir basin should not exceed one-fifth of that irrigable by the storage, so that the loss of land revenue due to the submergence of the former will not be a large percentage of the gain in return resulting from the irrigation of the latter.

CHAPTER XXXIV.

PHYSICS OF LARGE ALLUVIAL INDIAN RIVERS.

To the professional instincts of an irrigation engineer perhaps nothing appeals more than a large alluvial river. Its immense size, its enormous discharge, its apparent irresistibility, and its incessant variability, all impress him with a sense of his own impotence. Although these destructive characteristics are the first to strike him, he afterwards realises its beneficial ones—that by the silt it brings down from untilled and inaccessible heights it is the creator of new culturable lands, and that it alone enables these to be irrigated by its fertilising water. Then he remembers that while his predecessors may not have succeeded in completely harnessing the mighty current, they have still been able to hold it at their weirs, to prevent its overflow by their flood embankments, and to divert what supply is required into their canals, whereby prosperity has been conferred on lands which Nature left as desolate wastes. Lastly, he must reflect that it is his duty to continue the good work of adapting the gifts of Nature for the use and convenience of Man, and, by the aid of science and the experience of the past, to improve on and extend what has previously been accomplished.

Large alluvial rivers in different countries must have many similar characteristics, especially in their lower sections, but their behaviour is doubtless affected by the geological and meteorological variations of their catchments. What is written below is therefore limited to those of Upper India that take their rise in the vast Himalayan range, from which they emerge as roaring torrents bringing down large boulders and trees. Thereafter, they traverse extensive plains with a greatly reduced and generally decreasing gradient, and in many roughly parallel side channels carrying detritus, varying from small gravel at the head to coarse sand at the tail. Lower down the rivers have more defined main channels and their water is charged with fine sand. Finally, near their outfall, the sea, they form deltas through which they discharge themselves in numerous divergent channels bearing the finest description of pure silt. Although these rivers are not the largest in the world, owing to the torrential rains and steep slopes at the heads of their catchments, their flood discharges are extremely great. The maximum floods in cubic feet per second observed on the following bear this out—the Irrawaddy at Prome (150,000), 1,900,000; the Ganges at Rajmahal (368,000), 1,800,000; and the Indus at Sukkur (310,000), 900,000: the figures in brackets are the catchment areas in square miles. Compared with them the flood discharges of the Severn at Worcester (2,050), 40,000; the Thames at Staines (3,086), 14,794; and the Shannon at Killaloe (4,571), 26,667 are insignificant.

The leading features of an Indian alluvial river are the insufficiency of its channel to carry the largest flood discharges, and the great amount of silt which is suspended in the water. The result of these is that when the river is in flood it tops the banks, and the muddy water pours over them; as the velocity of this becomes greatly reduced, the water at once begins to drop its silt, in quantity gradually lessening as the overflow becomes clearer and clearer the further that leaves the river. In the course of time the country is thereby formed with very gentle slopes downwards from the river, which thus runs along a ridge, instead of in a valley, as is the case with an ordinary non-alluvial river. This creates a very dangerous situation, and sooner or later the river breaks through one of its banks and assumes a new course, where the same action is maintained, and a valley is thus formed between the old and the new river channels. Later on the river bursts into this valley and raises it by its silt. The process is continued, and thereby the river is enabled to raise and reclaim a much wider belt of country than that immediately bordering it. Even when on the whole it has attained a more or less permanent course, it stills pours silt on to the country during floods and raises it. This raising might then be restricted to a comparatively narrow strip, but for the constant changes of course of the natural, unembanked river, whereby old land is cut away, first on one bank and then on the other, and new land is thrown up on the opposite bank. Thus the width of the natural reclamation by the raising of the country is largely increased by the wanderings of the river. The extent of these wanderings (p. 151) is, however, controlled generally by the combined effect of all the varying factors which influence the course of the river, and that will be confined within the wide limits thus produced. Except when there is a complete change of course, which very rarely occurs, the river is not likely to exceed those limits, but within them it is probable it will continue its meanderings, and from time to time will first invade, and afterwards raise, the areas it had previously abandoned temporarily. In Upper India the low-lying riparian land is known as the *khâdir*, and the bordering high land as the *bár*.

It is the silt suspended in the river which makes its waters so valuable to the irrigator, but adds to the difficulties of the engineer. It is of very fine, unstable character, and as it constitutes the whole of the newly forming land, the river flows in a channel having its bed and sides of material quite unable to resist any violent attack by the current. If, however, the discharge of the river remained constant, a more or less permanent régime might be attained, but this is prevented by the great variation of its flow. During a maximum flood the river may have a discharge fifty to one hundred times, a width ten to twenty times, and a velocity and silt burden many times what it has during its lowest fair-weather stage. Not only are the floods excessive, but they vary in amount and duration, and by their great fluctuations are constantly altering the conditions, and thus become the principal disturbers of the régime of the river. Their effect is intensified by the silt they carry, as that is then present in its maximum amount, and is deposited on the bed as bars wherever the river curves change in direction. It is these bars that lead to the formation of overflow side channels, which during the inundation season may increase to become new main channels and to cause the abandonment of the old ones, thus altering the whole course and régime of the river in the locality by the cut-offs thus suddenly produced. To preserve that régime is the object of river training, the great principles of which have thus been stated : " Never throttle, always close, and work with a full head." In other words, the main channels should not be narrowed, the side channels should be blocked to prevent their increase and the formation thereby of cut-offs, and the main flood discharge should thus be induced to scour away the bars and pass down the low water channels in order to maintain them throughout the year. The method of training these large rivers is a most interesting subject of which the best Indian theory has been advanced by the late R. A. Molloy,[1] after many years of careful

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[1] Government of India Technical Paper, No. 118. (Central Printing Office, Simla.)

investigation, and of which the best original account in connection with the construction of large railway bridges, has been given by Sir Francis Spring, K.C.I.E.[1]

The factors which cause the great variation of the river's course may be divided into two classes—inducing and induced. Among the former may be placed gradient, velocity, curvature and high flood-level, and in the latter, erosion, scour, swirls and silting. All these more or less inter-act on each other, but a few distinctive features of each may shortly be mentioned. The steeper the gradient, the greater the velocity, erosive and scouring power of the river, and its tendency to alter its course. Taking long lengths into account, the gradient of the river is practically permanent, but in short ones is continually changing by the effects of scouring and silting. The velocity varies with the gradient, the cross-sectional area, and the nature of the bed and banks of the river, but depends chiefly upon its depth. The river has to adjust its velocity to what its bed and banks can stand. When the velocity is retarded, silt is dropped ; when it is increased, that is picked up. The curvature of a bend depends upon the cohesiveness of the banks, the fineness of the bed sand, the cross-sectional area, and the velocity and set of the river. Where curves occur, the river is in a more unstable condition than it is in straight lengths : the latter should therefore be selected for the sites of weirs and canal heads. At a "horseshoe bend" the curve nearly returns on itself, and the difference of level at its ends is at a maximum ; if this induces the river to form a side channel between the two, a "cut-off" may eventually be produced, and this will locally change the course of the river and cause it to assume a most unstable condition. The high-flood level of an alluvial river depends principally, but not entirely, upon the maximum rate of discharge, as does that of a non-alluvial river. It is quite possible, however, in the former for a smaller flood to rise higher than a larger one. Scouring of the bed and straightening of the course will lower the level, while silting and increased tortuosity will raise it.

Erosion is the destructive effect caused by the river's lateral action on riparian land and works, and is due to the local lowering of the surface and the bed. It depends upon the velocity of the river, the duration of its flood-flow, the nature of its bed and banks, the angle of attack, and the general alignment of the

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[1] Government of India Technical Paper, No. 153. (Central Printing Office, Simla).

bank, whether straight or curved. Scour is the destructive effect caused by the river's vertical action deepening its bed: it may induce erosion, or may be induced by it. It depends chiefly upon velocity, but also greatly on the deficiency of silt in the current, enabling that to pick up material from the bed. It is thus worst during a falling river, as then the water has little silt in suspension. Its total effect results much from the duration of the time it is in operation. A swirl is a rotatory eddy produced by a forward-moving current brushing past still-water, which thus gives the flow a circular motion: projecting spurs, causing dead water, thus lead to swirls. Swirls depend for their destructiveness upon the velocity of the current, the area of still-water, the size and nature of the sand of the river bed and banks and the duration of the flow. They are the most dangerous form of erosion, and protective works should therefore be designed to avoid them, and certainly not to produce them. Silting is caused by the deposit on the river bed of detritus from the catchment area, or that derived from local scour or erosion. It takes place when the water is charged with more silt than its velocity will carry forward; thus a rising river with a large silt burden silts up low places in the river bed; silt is dropped when the velocity of the river is retarded. The bulk of the silt is continually passing downstream, and thus the soil conditions of the bed and banks are constantly changing. The balance is carried by muddy overflows on to the marginal land, and usually consists of the finest clayey particles, which, when deposited, make sweet fertile soil.

The delta of an alluvial river is formed near its outfall into the sea: there the main channel divides into two or more branches diverging from each other. These in their turn bifurcate into smaller ones, between which are drainage lines, more or less defined and continuous, that result from the silting of the country gradually diminishing inland from the channel banks. All these channels have extremely meandering courses through the alluvium previously deposited, flood discharges in excess of what they can carry, and ones gradually diminished downstream by spills over their banks, except when a channel is fed by an overflow from a neighbour. Throughout the delta the discharge of the channels is affected by the ebb and flow of the tide. During high tides the water in them overflows the banks and submerges the land, thereby forming natural reservoirs which are drained during the succeeding ebb tides; the water thus impounded gives the channels increased scouring power to maintain their courses. This natural process can be aided by regulation of the discharges of the channels, so that these may not be increased by scouring and overflows, nor lessened by silting, and may thus preserve their courses unaltered ; this constitutes a desirable improvement. The embanking of the marginal land (see p. 149) to enable it to be cultivated by shutting out floods is, on the contrary, a highly disadvantageous arrangement which should not be attempted. It prevents the protected land from being gradually and regularly raised by silt—Nature's method of reclamation—and lessens the scouring power of the channels by reducing the reservoir areas caused by submergence. It will lead eventually to the formation of low-lying insalubrious tracts, always liable to inundation by breaches from the river channels, and will thus involve great danger so that it should not be carried out.

CHAPTER XXXV.

ALLUVIAL RIVER EMBANKMENTS.

IN the preceding chapter a description was given of how mighty alluvial rivers continue their careers of creators of new land. While in one sense this process is rapid, in another it is slow compared to man's short existence, and he therefore endeavours to hasten matters in order that he may occupy and cultivate that land as soon as possible. It was stated on p. 148 that he should not interfere with Nature's method of reclamation in the delta by embanking the river channels, but that he can assist her by regulating and maintaining those channels themselves. Upstream of the delta the conditions are more settled, but are still naturally too severe and variable to permit of the pursuit of agriculture on a large scale. During the height of the inundation season the river's discharge is beyond the capacity of its channel, and the flood water rises over the country and submerges it. It passes over the gentle slopes previously formed by the deposit of silt, but not in regular sheets as at places it concentrates into defined flood channels which scour out their beds, constantly change their courses, and cover large areas with infertile silt. Although it would be difficult to raise crops in the areas subject to inundation, at more or less uncertain dates, for periods of indefinite duration, and for unknown depths, hardy and vigorous riparian vegetation, adapted to the natural conditions, would flourish and become another obstacle to cultivation. If, however, the floods are confined by river embankments, the areas inland of these are protected from damage, can be cultivated, and can be irrigated by canals drawing their supply from the river, which is thus changed from a destroyer to a benefactor.

When the original cultivators began thus to protect their individual lands, they formed ring embankments around them, and constructed these as close to the river bank as probable safety from erosion permitted, in order to get a conveniently near water supply. In course of time the ring banks of neighbouring cultivators were joined together to form continuous river embankments. Thereafter, these were taken over by Government and strengthened and improved, but the alignments close to the river, were not materially changed as the lands in the immediate rear were cultivated and had to be protected. Thus at first the embankments were constructed only to safeguard individual interests, and the effect of their proximity to the bank on the régime of the river was probably not considered. That effect is to deprive the river of its natural flood escapes, the spills over its banks, and thus to increase its flood discharge downstream. Owing to these spills the river in its natural state has a continuously diminishing discharge as it proceeds, and in consequence adapts itself to this condition by gradually increasing its gradients. When, however, the spills are prevented and the flood discharge is thus increased, these lower gradients become too steep for the soils concerned, and to flatten them the river has to lengthen its course, which it does in the only way practicable by increasing its tortuosity. This leads to erosion of its banks which continues until more or less permanent conditions are re-established : until this happens, the wanderings of the river are intensified and may take place in an unforseen way. The result is that the near flood embankments are frequently attacked and destroyed, and have to be replaced by other embankments retired inland, and these, in their turn, may also be washed away. When aligning these new banks, in addition to getting security for them, consideration has to be paid to the desirability of protecting as much of the riparian cultivated land as possible, and at a cheap rate. Unfortunately, owing to the gentle slope inland of the country, the more a bank is retired the higher, more costly and more liable to breaching does it become. The tendency therefore is to limit the retirement as much as the acquirement of probable safety from erosion allows, and the extent of the river's attack is thus sometimes under-estimated.

Other objections raised to river embankments are :—

(i) They stop the gradual raising of the country by silty overflows ;

(ii) They deprive the areas inland of them of fertilising silt ;

(iii) They prevent those areas from being washed free from subsoils salts which rise to the surface by capillarity ;

(iv) They cause the river bed to be raised by silt ;

(v) They raise the high-flood level of the river, chiefly by preventing spill, but also by the increased raising by silt of the narrowed marginal land ;

(vi) By inducing greater tortuosity of course they lead to the erosion of cultivable land and the formation of sterile land by accretion of sandy areas opposite.

The first three refer to damage to surface conditions, and thus to cultivation, and the others to detriment of the river's régime. Of them (i) may be admitted, but the process is extremely slow—the valley of the Nile (the silt burden of which is, however, reduced by the large lakes at its head), is said to have been raised during historic periods only at the rate of four inches a century. Nos. (ii) and (iii) do not much apply to irrigated land which is silted and leached by irrigation. The last three objections are not agreed to by some engineers, who consider that, although at first they are valid, yet when the river has obtained a settled régime it will adjust itself to meet the altered conditions, chiefly by the deepening of its main channel by scour. In fact, river embankments on the Mississippi and Danube have been constructed with the object of thus improving navigation by the removal of shoals. However, it is doubtful how long the unassisted river will take to acquire its altered settled régime, and until it does, the last two objections appear to have considerable force.

The position therefore seems to be that, if on the one hand the river is left unembanked, cultivation, if not impossible, will be rendered difficult, as there will not be those settled conditions which are absolutely necessary for successful irrigation. If, on the other hand, the river is closely embanked, its régime will be altered for an indefinite number of years, during which its wanderings will be increased, and will lead to the destruction of the embankments (in proportion to their nearness to its channel) and to the damage of the lands surrendered by further retirement. The solution of the problem appears to be to adopt a middle course, and the one suggested is to construct the embankments on an alignment sufficiently retired as practically to gain permanency. It was pointed out on p. 144 that there are wide limits to the wandering of an alluvial river which are not likely to be exceeded, and the nearer to them is such an alignment, the more secure it will be. Many advantages will accrue from such a retirement in that it will practically restore the natural conditions to the river. The embankments will become more solid during their long life, and as time will be afforded to construct them slowly and carefully, it should be easy to make them breach-proof. Greater permanence will be afforded to irrigation, and the longer security thus obtained should lead to increased prosperity of the irrigators. There are, of course, disadvantages attendant on retirement. First, there is the increased cost of the embankments on the lower alignments : against this may be set the saving of the cost of replacing eroded embankments by new ones. Next, there is the greater height of the embankments making their failure should it occur more disastrous, but, after all, that height will not be considerable, and sound construction will make the earthwork secure. Then the open canal heads between the river and the embankment will be longer and the silting in them more extensive : some form of temporary silt regulator should meet this difficulty. Lastly, there is the reduction of the cultivated area : there is usually much ground available for irrigation inland of the embankments—failing this, the riverain area might be grown with post-inundation crops, or have forests established on it.

The advantages of retirement should generally outweigh the disadvantages. A further improvement may be practicable by constructing reclamation cross banks projecting towards the river from the main embankment to cause the formation of a silted foreshore there. These banks might afterwards be increased in length and section to form cross embankments having their river heads in a general sinuous alignment and formed as Denehy's groynes to resist erosion. These would hold the river to a parallel course, whereby it would be given greater tortuosity, thus reducing its longitudinal slope, velocity and erosive power, and thus conferring on it a settled régime.

CHAPTER XXXVI.

DISTRIBUTION SYSTEMS.

In a canal system the arrangements for distribution convey the water from the source of supply on to the irrigated area. The principal parts of the canal system are—first, the *canal* which is the main line ; it leads from the source of supply and feeds the *branch canals*, or direct, the distributaries of the distribution system. The *distributaries* are the next larger lines ; they pass the water from the main and branch canals to the minors, or direct to intermediate watercourses. After them come the *minors* (more correctly these should be termed " minor distributaries "), which are smaller channels led from the distributaries to supply the watercourses. These four classes of channels in India are constructed, maintained and controlled by the State. Finally are the *watercourses*, or field channels, which are the very small channels that actually pass the water on to the irrigated land. The distinction between the canals, main and branch, and the distribution system therefrom is one, not of size, but of function. The former in large schemes are not provided with outlets for the direct irrigation of the fields, whereas the channels of the latter are supplied with outlets for such irrigation. Small canals irrigating directly are thus really distributaries.

Loss in transit from evaporation and absorption occurs in every part of the system, and in the Bari Doab Canal experiments were found to average 20 per cent. from the canal head to the distributary head ; 6 per cent. thence to the irrigation outlet ; 21 per cent. in the field channel ; and 25 per cent. in wastage at the outlets and by irregular distribution. Thus of the whole initial supply the losses ascertained were 26 per cent. on the Government channels, and 46 per cent. on the irrigators' channels and wastage, leaving as balance 28 per cent. actually utilised on irrigation. Every reduction of this loss is of great importance, for a saving on it of 1 per cent. will increase the irrigated area by practically 4 per cent. The Government channels should, therefore, be aligned so as to pass by the shortest course practicable, through the most retentive soil available, and where they are in pervious strata, should be made staunch. They should be led close to the irrigated area so as to reduce the length of the watercourses, and it is desirable that these should be properly aligned and constructed by Government agency at the expense of the irrigators, or if this cannot be arranged, by the irrigators themselves under Government supervision. Not only must all these channels be correctly set out and executed, but they must continuously be maintained in good régime, as every obstruction to flow increases loss by absorption. The engineer's administrative authority ends at the outlet heads of the watercourses, but he should exercise his influence over the irrigators in respect to the maintenance of their channels, economical irrigation and, particularly, the avoidance of waste.

The history of irrigation in India shows that the importance of a good distribution system, constructed complete to utilise the supply as it was made available, was not at first recognised. The early engineers were professionally more interested in executing the grand works which furnished the supply, and neglected the humbler ones required for its distribution. Thereafter, comparatively small sums were allotted to the development of the distribution system, so that sufficient revenue was not earned on the costly main works, and thus interest charges mounted up. Moreover, that development took place in a haphazard way, and not on a pre-arranged and well-thought-out plan. The old watercourses belonging to individual proprietors were at first continued in use, and the construction of others encouraged by the grant of advances, which were sometimes misapplied and frequently utilised wrongly. The first improvement consisted in the reduction of the number of outlets and long irregular watercourses, and in the provision at Government expense of more minors, leading the water in proper channels close to the irrigated lands, thus reducing the length of the watercourses, and advice as to the construction of these was given to the irrigators. The minors, however, were often badly aligned with only their own objects in view and not as parts of a complete system. The final improvement was the development of the system of minors, to fit them into a proper system of distribution, and to align them correctly along, and not across, the small watersheds traversed. Outlets were further reduced in number, located where required, and varied in size in proportion to the areas irrigable by them, and this process is being continued. Further advice as to their watercourses was given to the irrigators, and many were induced to pay for their construction by Government agency. As this evolution has progressed, so also have increased the benefit to the irrigators, the irrigated area, and the revenue therefrom.

Not only must the irrigation system be correctly designed, executed and maintained, but it must also be properly worked: in India the constructional development sketched above has been accompanied by an administrative one. At first, with numerous proprietory outlets from the main canal and its branches, control was very difficult. As these outlets were closed and for them were substituted Government ones at intervals along the minors, so working arrangements improved. The difficulty experienced was due to the great number of the outlets still remaining; the rotation of supply to them had perforce to be left to a great extent to the subordinate staff. The final stage was reached when the number of minors was increased and that of the outlets was reduced, and their sizes regulated to the extent of the areas served by them. It then became possible to run the minors at their full-supply discharge under a system of rotation, fixed by the superior staff, for periods according to settled time tables, during which all outlets from each feeding channel were allowed to be opened full by the irrigators without official interference. This change resulted in the greatest improvement ever made in canal administration, as thereby control was placed in impartial and expert hands, supervision and wastage were lessened, and the irrigators freed from oppression. Further benefits resulted from it—a reduction of the canal staff; the maintenance of the proper régime of the channels with their designed full-supply discharge and velocity preserved, thus reducing silting; reduction of seepage and evaporation while the channels were dry; prevention of the loss by leakage at numerous outlets during the periods when their minors were closed; the stoppage of the unauthorised use of water at outlets not entitled to supply during the rotation; and fair distribution to all irrigators from the head to the tail of each minor.

The main administrative measures required to obtain the best distribution system have been noted above; some engineering principles will now be described. The best alignment consists of long straight lines connected by short, regular curves so as to avoid great differences of ground level. It should get on to the watershed as soon as possible, and thereafter should keep to it, in order to obviate the necessity for cross-drainage works and to secure irrigable command of land on both sides. Difficult country should be avoided, *i.e.*, that having ridges, depressions or watercourses, or consisting of rocky, pervious, alkaline or waterlogged strata. Good watertight formations which can easily be excavated should be preferred. The more the cross-section balances excavation and embankment, the cheaper will it be: deep cuttings and high embankments should therefore be avoided. Each channel should be as central as possible, and should be able to irrigate its whole command without assistance from another. The more, within reasonable limits, the system of distribution is subdivided, the easier will it be to regulate supply. As the larger is a channel the more economical proportionally are its construction and maintenance, the best arrangement is therefore to have large distributaries and numerous minors of fair, but not too small, size.

In regard to velocity, at the head of the system the main canal and its distributaries and minors should have a rate of flow equal to V_0 (Kennedy's critical velocity—non-silting and non-scouring), or slightly exceeding it, but never less than it, or silting will occur. As draw-off occurs by minors along a distributary, or by outlets along a minor, and the silt content of the water is thereby diminished, so may V_0 be gradually reduced to $0.75\ V_0$ at the tail. This will cause a deposit of fine mud in the lower lengths which will staunch them.

The grading of the different parts of the distribution system should be varied to secure the velocities desirable for them: this will not only waterproof the lower parts by silting, but will make their water surface more parallel to the slope of the country: that surface should give good command to the smaller channels served. The beds of minors should be near the ground surface so as to command the marginal fields by flow.

In respect to section, the average depth of minors should be from one-fifth to one-seventh of the width for small channels, and the proportion of depth made smaller for large channels. Shallow and wide channels save both capital and maintenance costs of masonry and earthwork, owing to the lessened height of the banks, and they also reduce the variation in water level due to fluctuations of discharge. Changes of bed width should be made below sites where water is drawn off, usually by six inches for small channels, and by feet for large ones. Changes of depth may also similarly be effected, but generally by much smaller amounts.

The discharge of each part of the distribution system should be calculated in accordance with the area irrigable thereby, the duty allowed, the loss in transit, and the time during which the section will be in flow, which, as a rule, should be half the whole time. In India the maximum discharge is required during the monsoon, and the sections of the channels should be calculated to pass it.

The full-supply level should not be very high, as this will increase the cost of the banks and their liability to breach. The maximum full-supply level should have good, and the low full-supply fair, command. In main channels the full-supply is usually kept from 1.5 to 2.0 feet, and in minors 1.0 to 1.5 feet, above ground level. The ordinary height of the top of the bank above full-supply level is for large channels 2.0, *plus* the allowance for settlement, for small ones 1.5 feet, and for watercourses about 6 inches.

Silting berms are necessary where the full-supply level is high above ground surface. To form them the canal banks are set back, usually by an amount such that a line joining the top inner, or canal side, edge of the final berm with the bottom of the outer, or land side, toe of the canal bank will be at an inclination of at least one in six.

PART II. WATER SUPPLY.

CHAPTER XXXVII.

SMALL PROJECTS.

WATER supply schemes are required to increase the health, convenience, trade facilities and safety of the population served by them. The first object is concerned with drinking supply and sewerage; the second with domestic and public requirements; the third with manufactures; and the fourth with fire extinction. The character of the waterworks indicates the degree of civilisation which the population has attained: that will be highest in large urban communities for which the provision of supply for all the objects mentioned above must be made. Small urban communities, decreasing in size to villages, must for financial reasons often be satisfied with less perfect schemes. The water supply requirements of the latter towns are therefore complicated, and to discuss them fully would involve much writing: that, however, is unnecessary here as they are dealt with in many excellent treatises. The needs of smaller towns are less complex, and are thus often not catered for by such books: in this and in a few succeeding chapters are therefore mentioned some principal matters which require attention in their case. In these latter towns the chief object to be aimed at will be the improvement of the health of their inhabitants, for a sufficiently good organised supply is of vital importance, especially in the East, where the people are peculiarly exposed to sudden, devastating water-borne epidemics, such as cholera, against which an uncontaminated water supply is the only preventive. The other objects can be satisfied as the small community increases in numbers and wealth, and this will probably result from the original provision of good drinking water. Such small schemes should provide sufficient quantity of water of good quality; should be expansible to meet future requirements, reliable in construction, and simple in maintenance; and should not be very costly.

Quantity has been placed first in this list, although many give quality the priority. The reason for this preference is that unless the quantity of supply is sufficient, the waterworks may be supplemented from contaminated sources, and then from the protective point of view their utility will to a great extent be destroyed. In regard to quality, which is of course of the utmost importance, the designer of the scheme will naturally have secured a good potable supply, and any minor defects in it can be made good by treatment. The determination of the quantity required by small communities is comparatively simple as it depends only upon the number of the population, the consumption rate per head, the time during which the supply must be self-sufficient and an allowance for waste. It will generally be ample for them to provide for 25 per cent. in addition to the existing inhabitants, and to allow a daily supply of from five to ten gallons a head in accordance with their style of living. The duration of the supply is a matter of great importance, and can be properly ascertained only by a long period of observation, for which reason as soon as a scheme is mooted gaugings should be started. If, however, the time for investigation is short, the results obtained on neighbouring schemes should be utilised and compared with those of the new scheme during the period in which gaugings for both are concurrently conducted. In England storage reservoirs are made with a capacity varying from 120 days' supply in the north to 250 or more days' supply in the south. In the tropics it will be best to double these figures, according as the reservoir is situated in an area of certain, or in one of uncertain, replenishment. When the source of supply there is from a stream, its discharge at the end of the fair weather should be equal at least to three times the rate of consumption : when it is from a spring its then flow should be at least half as much again as that rate. Waste is either unpreventable or controllable. Under the former head come losses by evaporation and absorption in storage reservoirs and losses in transit down supply conduits : liberal provision should be made for these in the project. Under the latter are losses in distribution, which for simple works should not be great if the draw-off for consumption is duly supervised.

Quality is a most important consideration : not only must the water be of good quality at the source of supply but it must be delivered uncontaminated to the consumer. It is true that minor defects may be remedied by various treatments, but all of these involve extra expense in maintenance and require skilled application ; thus inferior water is generally not suitable for a small supply. For such, a naturally pure water should be chosen so that it requires nothing more than the simplest treatment to render it potable. Examined physically, a good water should be free from colour, odour, objectionable taste, deposit and turbidity ; should possess a clear, sparkling appearance ; and should have a refreshingly low temperature. All water is originally derived from the rainfall, which is the result of natural distillation (evaporation) and condensation, so that it starts practically pure. It is, however, greatly liable to contamination by noxious gasses and germs, if they are present in the air, and to deleterious salts and germs, if they exist on the surface of the ground or in the subsoils. The engineer should first examine a water as to the physical qualities noted above, and if it possesses them, he should carefully inspect the gathering ground from which it is derived, and should satisfy himself as to the sanitary condition of that, or to the possibility of improving it by the diversion of sources of impurity. This preliminary examination should lead to the rejection of palpably bad supplies, and when properly conducted will rarely not be confirmed by analysis, which is the next step to be taken. There are various forms of analysis—chemical, bacteriological and miscroscopic—and all should be conducted by an expert chemist, who should be consulted as to the samples he requires, and should be given all local information necessary for him to arrive at a correct interpretation of the results of his examination. Samples sent to him should be truly representative of the water to be examined, and should reach him as soon as possible after they have been obtained to obviate deterioration by storage. The bottles containing them should be perfectly clean, and finally, should be rinsed in the water to be tested. Glass stoppered bottles are the best, but if not available, tightly corked ones may be used and should not be sealed with wax or paraffin as these may introduce matters which will distort the analysis. The engineer should be able to understand the analyses, to see if it is, or is not, practicable to remedy any defects of the water thus brought to notice, and, to make his own reasoned recommendation as to the acceptance, or rejection, of the supply.

Expansibility of the scheme is most desirable because its enlargement will probably become necessary by the increase of the inhabitants of the town, and by the larger use of supply by individual consumers as its utility becomes realised by them. Since works of expansion generally involve reconstruction of parts of the original structures, the latter should be sufficient to meet the likely requirements of the first twenty years, and should be designed to let future enlargements be as cheap as possible. To make greater provision than this would entail more original capital expenditure, leading to enhanced maintenance costs, which would bear hardly on the first beneficiaries. To estimate what will be the probable growth of consumption, comparison should be made with similar-sized, characterised and situated towns already provided with water supply schemes. If a project is not itself expansible, and increased demands in the future have to be met by the construction of supplementary works, both the capital and maintenance costs of the combined system may be unduly increased, and its operation rendered more difficult, than would be the case were the original works themselves expansible.

Reliability of construction is essential and especially for the larger works of the scheme, for should these fail, their reconstruction will probably be slow and costly. During the time the supply is discontinued, or even restricted, the inhabitants of the town may be put to great distress, as then their original water arrangements may have deteriorated, or ceased to exist by disuse, while at their best they were inferior, or they would not have been supplanted by the new waterworks. For these larger works absolutely no risk must therefore be run and they must accordingly be designed and constructed so as to ensure perfect security. Even for the smaller works equal reliability is desirable, but when their repair can be effected in a short time, or a high class of construction will entail greatly increased capital cost for the whole scheme, less perfect arrangements may be justified. In these cases continuity of supply should be attained by having near the town temporary storages of such capacity as will be ample to tide over the time required to effect repairs of minor works. Such storages are, anyhow, necessary to enable ordinary maintenance and repairs to be executed ; their provision will aid in the purification of the supply, as well as act like safety valves to the whole system.

Maintenance consists in provision for the proper upkeep of the works of the system and for its operation. In regard to upkeep it is advisable to reduce maintenance expenses as much as possible, if necessary by an increase of capital expenditure, even if that may amount to somewhat more than the capitalised value of the saving, as this will add to the security and efficiency of the whole project. Upkeep also involves replacing parts which have to be renewed owing to decay : to arrange for this, provisions for depreciation have to be set aside, and these depend upon the life in years (as noted in brackets) of the different parts, for which allowances are—

Masonry and earthen dams and embankments (perennial) ; cross-drainage works (100 to 200) ; buildings (100) ; cast-iron pipes (30 to 75) ; riveted pipes (20 to 50) ; hydrants, valves, etc. (15 to 30) ; engines (15 to 25) ; boilers (12 to 20).

Thus non-metallic parts (which will form most of the expenditure on small schemes), are much less costly to maintain than metallic ones. Simple schemes, such as gravitation ones, which will usually be constructed, will also be cheaper in cost of operation than complex schemes which necessitate pumping, as that is much the most expensive item in working.

The cost of the scheme will depend upon—

(i) The capital, or original, cost of the works.

(ii) The annual maintenance cost of working expenses and ordinary repairs.

(iii) The cost of special repairs and renewals at intervals.

(iv) The sinking fund to cover the capital cost in a certain number of years (usually from thirty to sixty) at compound interest.

To compare the cost of one alternative project with that of another, (ii) to (iv) should be capitalised and added to (i)—the scheme for which the grand total is smallest will be the cheapest. A certain degree of preference should, however, be given to the one with the smallest amounts for (ii) and (iii) as these items are more liable to under-estimation than are (i) and (iv). The cost of a water supply scheme is usually borne by the population, etc., served by it, but as this is generally great, in some backward countries State assistance is given, when without it the project could not be financed, so that progress in sanitation may be effected. In such cases every economy practicable is necessary, and the scheme might at first consist of storage or intake, supply limited to a small rate of consumption, an open channel, or simple masonry, etc., conduit, an open service reservoir, and a few distributing mains with a street service for consumption. As time goes on and funds permit, the project could be improved, and it should therefore be designed originally so that the improvements can be executed with the smallest expenditure practicable on reconstruction or replacement.

CHAPTER XXXVIII

SOURCES OF SUPPLY.

WHEN choosing a source of supply for a small waterworks, regard should be had to its reliability, sanitation, simplicity, convenience and cost. Reliability consists in its giving a sufficient supply constantly, for its failure in this respect will, if partial, cause much inconvenience should the rate of consumption have in consequence to be reduced, and great danger, if complete, as then the population will be driven to resort to their previous inferior supply. Sanitation includes a clean gathering ground which is not liable to be polluted, and a protected line of supply therefrom which will preserve the water from contamination. Simplicity requires works which can easily be constructed and maintained, and ones which can be managed without difficulty. Convenience is assured when the works are near the town and can thus be supervised properly by the superior staff. Cost should take into account both original capital expenditure and annual charges for the maintenance of the works and in operating them.

A storage reservoir has certain great advantages. By locating the dam where the catchment is sufficiently large, it should be possible to secure a supply which will last until it is practically certain future replenishments will restore it. Then the water is in sight, so that if a partial failure of replenishment occurs, the maximum amount of time practicable will be afforded to concert temporary measures for supplementing it. Ordinarily, a reservoir is situated in upland country which is sparsely inhabited by men and animals and is not much tilled ; when that is the case its sanitary condition is naturally good. By acquiring an area considerably larger than the high-flood contour and fencing or hedging its boundary, the risk of occasional contamination throughout the fair weather will be slight. In this connection it is advisable to form fenced watering places for the marginal population, as remote as practicable from the outlet, so that promiscuous fouling of the foreshore may be avoided. As the feeding stream is likely to have a flow of short duration, when it ceases there will not be any outside drainage to contaminate the supply. Of natural purifying agencies the most effectual is sedimentation and this takes place to the largest extent in a reservoir, where the water remains quiescent for months and does not then receive sensible further contamination. Not only are sedimentary matters thus precipitated, but they also carry bacteria with them to the reservoir bed, where these die from want of light and food. A reservoir, however, sustains much loss of water by evaporation ; to reduce this loss as much as possible, it is best that the basin should be deep with fairly steep banks, *i.e.*, its cross sections should be concave, not convex. This will both increase and improve the storage by lessening evaporation and the amount of bottom water which should not be drawn upon, and as the surface falls, the extent of the marginal area laid dry, and will increase the depth, and thus the effect of sedimentation. For a small town it is desirable that it should be commanded by gravitation so that it may be supplied by flow, and thus avoid the expense of pumping. This may involve the location of the reservoir some distance off, and thus add to the length and cost of the supply line. If a near site has only a slightly deficient elevation, it may be financially practicable to raise the outlet sufficiently to make good this defect. In regard to construction the dam may be an earthen or a masonry one, and as it is not likely to be high, both are equally good forms : the former will probably have the advantage of cheapness, and it will be easier to raise it should further storage become necessary. For most works when expansion is required, it is advisable to enlarge the original structures, rather than to supplement them by additional ones. In the case of a reservoir, however, the construction of a subsidiary storage has the advantage that thus the two basins can be worked alternately in the fair weather, the bed of one being laid dry during part of one year, and that of the other, similarly, the next year, so that thus they may alternately be ploughed up, desiccated and purified. Generally, it will be found that a storage reservoir with an earthen dam is the most suitable source of supply for a small town.

A lake is a natural reservoir and thus shares most of the water supply advantages of an artificial one, but there are points against it. It is probable that it will occupy the bottom of a fertile valley which will largely be inhabited and cultivated, and thus will have a less sanitary catchment than the latter. Its low elevation may prevent its affording a supply by gravitation. and the intake works may be costly to construct. On the other hand, it will usually be possible to increase the storage capacity at a cheap rate. Lakes seldom exist in India except in hilly regions, where, ordinarily, the population is too small for a water supply scheme.

A river intake is generally inferior to a storage reservoir from a sanitary point of view, as a river has an irregularly fluctuating supply, is liable to be polluted by storm water, and its banks to be fouled by men and animals; moreover, during the rainy season the water will not be purified by sedimentation. To make these defects good, a scheme from a river will usually require artificial settling basins. The higher up a stream the intake is placed, the purer is likely to be the supply, and the better its command, but the quantity will probably decrease and be available at more fluctuating levels. If practicable, a gravitation scheme should be aimed at. The greatest care must be taken to locate the intake where it will not be subject to sewage contamination. To lessen the deposit of silt and detritus at its site, that should be on the concave side of the stream, or on a straight reach, and the intake sill should be at some height above the bed. To test the sufficiency of supply, unless that is always in great excess of requirements at the end of the fair weather, gaugings of the discharge should be made for as many years as possible. One advantage of a scheme from a stream is that, should the supply become deficient, it should be possible to increase it by means of wells or galleries in the bank higher up.

A gallery taps underground flow, and if properly placed receives that after it has undergone natural filtration. It is usually formed by an open excavation of narrow width, sufficient for constructional purposes, and this is afterwards roofed over, is lined downstream by impermeable walling and is provided with a manhole shaft for inspection. Its length should be such that the flow induced to it is slow, for an excessive rate of draught involves certain deterioration of the quality of the supply. A great advantage of a gallery is that ordinarily it can be extended so as to keep pace with the growth of consumption. Often a gallery is constructed along the margin of a stream in order to get supply by percolation therefrom, but should not be nearer than fifty feet from the bank to ensure efficient natural purification. A disadvantage of such a gallery is that the rate of percolation varies directly with the amount of stream flow, and is thus least in the dry season when supply is most needed. To test that rate, several trial pits should be sunk on the line proposed for the gallery, and these should be pumped at the close of the dry season. In certain cases galleries have been driven under and across stream beds, whence the supply is likely to be most abundant. The depth of cover above them should be considerable, as otherwise the water, although clarified, may not be purified from bacterial infection.

A spring is an overflow of subsoil water supplied by percolation from the strata above it: the larger the underground catchment, other things being equal, the more permanent and regular will be the flow. As it is an overflow, it should not ordinarily have its discharge increased artificially, as that will lead but to temporary improvement, lasting only as long as it takes to lower the feeding underground reservoir. By such lowering that reservoir will, however, have diminished power to maintain the flow required. It is only when the subsoil water continues its course below, or to the side of, a spring that it should be tapped, either by deepening the shaft or by constructing lateral adits to it. Deep-seated springs in sanitary areas furnish good permanent potable supplies, but shallow ones in contaminated ground, dangerous and temporary ones. The sufficiency of a spring should be tested by gauging its discharge over a notch. Where there are several springs issuing close to each other, they can be collected together so as to keep pace with the increased demands of consumption. There are few places in India where springs can be utilised for water supplies.

Wells and boreholes tap subsoil water which is not brought to the surface by springs: compared with each other, the former are of large diameter and usually shallow, and the latter of small diameter and generally deep. Shallow wells in contaminated soil are dangerous: deep wells and boreholes are safe if surface percolation is cased off. Similarly to galleries and springs, they should not be drawn upon at an excessive rate. Both forms can be sunk in series and the series connected up, but it is better to have one large well than several small ones. The former will have increased storage capacity and will thus permit of pumping at variable rates, will give more space for the pumping machinery and concentrate that at one place, will reduce loss of head by friction, and will prevent the entrance of sand by the low rate of inflow. In all shafts the draw-off should not exceed the natural inflow, which is the amount of permanent supply that can be given, and pumping should therefore not unduly lower the level. The combination of shafts in series enables a scheme to be made expansible. Wells and bore holes are peculiarly useful for water supply schemes in alluvial tracts.

A village water supply is often obtained from the village tank, which is frequently in an insanitary area and is fouled both by man and beast entering it ; moreover, owing to its shallowness, it loses much by evaporation, and may not last throughout the fair season. A small but valuable improvement would be to excavate a deep pond in the tank bed and raise the dam with the spoil. The pond would preserve supply for a long time, and it would be useful for watering the cattle, for which purpose it should be dug with comparatively gentle side slopes, and have an approach road sloping, say at one in ten. It should be excavated some distance from the dam and not expose porous strata. For the supply of the inhabitants a small well could be dug on the downstream side of the dam and opposite to the pond, which would by percolation supply it with naturally filtered water. The well should be steined and provided with a pulley with bucket and chain for lifting the water, and near this the ground should be paved and drained.

CHAPTER XXXIX.

PRELIMINARY PURIFICATION.

THE only absolutely safe gathering ground would be one consisting entirely of uninhabited, uncultivated, unpastured and barren, insoluble soil, or rock. Such practically can never be found, and therefore to obtain a safe supply from a surface source it will be necessary to purify the water artificially. It is, however, most desirable to maintain the surface furnishing the supply in as good a sanitary state as practicable. That would be best effected if the whole gathering ground were acquired and placed under sanitary control, but this can seldom be done : it might, perhaps be possible to have it protected by legal enactment, preventing the increase of contamination and prescribing rules for sanitary conservation. Failing these, the engineer must rely on his own arrangements to secure as much protection as feasible. Ordinarily, the most harmful thing in a catchment is a collection of human inhabitants with their animals, and the pollution from these increases with their number and their nearness to the source of supply, or to streams draining to it. In the case of a reservoir, or lake, the least that should be done is to acquire a belt of ground beyond its high-flood contour, and to conserve this by hedging its boundary. It is impracticable to adopt this measure all along the course of a river, and that is one objection to obtaining supply from such a source. Land can, however, easily be purchased around a gallery, spring, well or borehole, and for them this should be done : if drains are cut along its boundaries, surface external drainage will be cut off and the enclosed area can be properly conserved.

In respect to reservoirs much improvement may be effected by diverting contaminated surface flow. Where it is possible to discharge that flow downstream of the dam or outside the catchment, this should be done, but, where an upstream village is situated some distance from the dam or watershed, this may not be directly practicable. Probably the best way to treat such a village built on a site remote from a stream is to surround it by a low embankment, or catchwater drains, and to lead its drainage into a small tank with a storage capacity equal to, say, one-fourth the maximum annual yield of its catchment. The tank could be emptied, say, four times a year, so that the whole of the drainage would pass into it, and it could be utilised for the irrigation of fields immediately below it ; if these were surrounded by a low bank, none of the contaminated run-off would find its way directly into the water supply reservoir, and that which would enter it by subsoil percolation would thereby be purified. If the village were on the bank of a small tributary, small intake weirs might be built, one upstream and one downstream of it. The latter would have from it a small channel leading into a small settling tank, as before, which would receive the highly contaminated washings of the village due to light falls of rain. The former would also have from it a small channel discharging downstream of the latter, and thus passing off small discharges due to light rainfall upstream of it, which would otherwise fill the settling tank too quickly. When rain fell heavily, both the village and upper catchment would at first be washed fairly clean, and the then discharge, being small, could be impounded as before, while the subsequent large run-off would not be much contaminated, and would pass direct to the water supply reservoir. These measures are best adapted to the tropics, where sanitation is defective and the rainfall heavy ; in temperate zones sanitation is superior and but little run-off results from the light rainfall.

The surface of the ground is likely to be charged with bacteria, as it is abundantly supplied with light, warmth and food for them. The subsoils, as they are lower and lower, have fewer and fewer germs, for the upper ones are strained out and the natural conditions are adverse to the development of fresh ones. During the construction of the reservoir every precaution must be taken to prevent the fouling of the future basin by the work people. Its bed should then be ploughed up and allowed to desiccate for as long as possible, so as to become purified, and all trees and bushes growing on it should be uprooted and burned. Similarly, every year as the surface of the reservoir falls, its dry margin should be ploughed up.

Even if all precautions are taken to improve the sanitary condition of a catchment, the large extent of its area and the numerous sources of pollution by men, animals and cultivation lead to the defilement and necessitate the purification of its yield :

this is effected either naturally or artificially. The principal natural purifying agencies are dilution, sedimentation, aëration, sunlight, germ competition, and occasionally, chemical reaction in flowing water. When sewerage enters a stream or storage, it becomes diluted with a much greater body of water, which, if more sterile, will diminish the growth of the germs. In gently running water the fine inorganic particles originally in it tend to fall to the bed and carry the germs with them, but if the flow is quick and turbulent, both organic and inorganic impurities are brought up again to the surface by eddies. If, however, the water is quiescent, the particles and germs are left on the bed, and the latter die from want of light and food. Sedimentation is thus the most efficient natural process of purification, and takes place most effectually in large storage reservoirs where that process is not interrupted for months : as sources of water supply they are thus much superior to those derived from streams direct. Aeration improves a water by its oxidising effect ; it occurs best in quick flowing streams and also when waves are produced by wind acting on the surface of a reservoir. Sunlight destroys certain bacteria by the action of its chemical rays : it is most powerful in the case of clear water. Germ competition arises between different kinds of bacteria : it is probable that these have each their own particular food, and that when they exhaust it and die, they destroy other forms by the toxic effect of their by-products. Chemical re-action will happen when a stream with salts and acids in solution acts on the soil through which it flows. Although these natural agencies are useful, they are likely to be irregular in their action and are out of control, so that full dependence cannot be placed upon them. To gain complete protection from hurtful matter, resort has therefore to be had to artificial treatments and these are, sedimentation and coagulation (preliminary), and purification and filtration (final).

Sedimentation, if sufficiently prolonged, reduces the number of all kinds of bacteria and devitalises those producing water-borne diseases ; it diminishes the amount of originally suspended matter ; it thus aids filtration, lengthens the life of the filters, and lessens the danger resulting from their breakdown. To take full advantage of it, at every stage of its treatment water should be drawn from a little below the surface, to avoid surface contamination, and not lower than a little above the bed, so as to be free from pollution by sedimentary matters. The process is carried on in settling basins, the size of which should be in proportion to the turbidity of the water ; thus, if the supply line is an open earthen channel, it should always have a large settling basin at its tail. To induce rapid sedimentation, the water in the basin should be kept as quiescent as possible. The rate of settlement depends upon the size and shape of the particles, since their weights are proportional to the cubes, whereas their surface areas vary as the squares, of their diameters. Turbid waters soon deposit the coarsest suspended matter, and this carries down with it finer particles and germs : the finest particles and other germs may remain suspended for months. Sedimentation effects the greatest removal of organic and inorganic impurities when the water is turbid, and the least when it is clear. The settling basins should not add to the turbidity by their own material, and except in the smallest schemes should therefore not have their beds and sides of earth, but of concrete and masonry, respectively. They should be formed in more than one compartment, so that one can be thrown out of use when it has to be cleaned. The shallower the basin, the quicker will the water be cleared, but the more costly will be the construction : from eight to ten feet will be a suitable depth for a small scheme.

Coagulation is the process required to complete the work begun by sedimentation : this it effects by the action of a chemical which produces a gelatinous precipitate that falls to the bottom at the rate of about a foot an hour. It is thus much quicker than sedimentation ; it is also much more efficient than it, as owing to the sticky nature and greater volume in larger masses of that precipitate, it carries down with it most of the bacteria ; it also reduces coloration when that exists in small amount in the water. The principal coagulants used are alumina sulphate, common alum (the double sulphate of alumina and potash), and ferrous sulphate. The first is the one chiefly employed, as coagulation depends upon the alumina, which is present in the simple sulphate to double the quantity that it exists in alum, and the former is as cheap as the latter. The coagulant salt may be placed on a tray in a solution chamber, and the water made to pass through this into the coagulating basins, which should be similar to, but smaller than, the settling basins. Even for small water supply schemes it is highly desirable to have both sets of these basins from the start : filtration beds can be added later when funds permit, more skilled manipulation is available, and a purer supply is required.

CHAPTER XL.

FINAL PURIFICATION.

AFTER the gathering ground and the water yielded by it have received preliminary treatment, the latter is rendered sanitarily pure by final treatment, which in its complete form comprises purification and filtration. Purification processes are carried out to remove from raw water dissolved constituents which may render it unsuitable for potable, domestic, or manufacturing purposes, or injurious to the distribution system. As they all involve care and skill in manipulation and increase capital and working costs, they are not likely to be installed in small waterworks in India, so that they will be noticed very shortly. For such systems, when a near supply is defective and requires purification, it is far better to go further afield and obtain a supply which does not necessitate such treatment.

Water which contains bicarbonates of lime and magnesia, held in solution by free carbonic acid gas dissolved in it, is said to have " temporary hardness," because by simple boiling the gas is driven off and these salts are precipitated. In Clark's process the same result is obtained by adding a small excess of lime (usually in the form of lime water), which combines with the carbonic acid to form carbonate of lime, and that is precipitated together with the salts previously held in solution by the gas. In Clark's scale each degree is equal to one grain of lime dissolved in one gallon of water. The untreated bicarbonates when precipitated by boiling impair the flavour of certain foods, cause a large waste of soap in washing by curdling it, and produce a soft deposit on the vessels or boilers holding the water. " Permanent hardness " is due to other salts of lime and magnesia (chlorides, nitrates and sulphates), which are not precipitated by the expulsion of carbonic acid gas dissolved in the water but are deposited as they become concentrated by boiling. They are removed by the addition of carbonate of soda, which forms with them soluble salts, and precipitates the lime, etc., as carbonates. Permanent hardness produces a very hard, compact scale in the vessels in which the water is boiled. Iron salts affect the taste and appearance of potable water and render it astringent. It may make iron mould appear on clothes washed in it, and cause the formation of tubercles in the distribution pipes which may seriously choke them. These salts can be oxodised by aeration and removed by filtration through sand ; if there is free carbonic acid in the water, it can be neutralised by adding lime ; if the iron exists as a sulphate, it can be treated with lime and alumina sulphate, or ferrous sulphate, or ferric chloride. Colour is chiefly due to decaying vegetation in water—vegetation should therefore be cleared off storage basins, etc. Extensive coloration should be dealt with by aeration or coagulation. Odours and tastes are generally caused by the decay of aquatic plants and animals, especially in hot climates. The water may be treated as for the removal of colour, or by copper sulphate which has a great toxic effect on the lower forms of vegetable growth, even when very dilute. This probably explains the action of copper vessels which have long been used in India to give protection against cholera and typhoid. Aeration reduces the defects produced by offensive gases.

Sterilisation consists in attacking impurities by chemical re-agents or by boiling. In India shallow wells suspected of infection by cholera are purified by stirring permanganate of potash in them and washing their sides therewith until the red colour of the solution remains permanent. After the coloured water has stood in them for some hours, it is drawn out, and, if necessary, the process is repeated. Simple boiling, without subsequent filtration (which may re-infect the water), is the best domestic treatment, as cholera and typhoid germs are killed by it in five minutes. The water should be allowed to cool in vessels, also sterilised by boiling, and when cool, may be made more palatable by aeration and the addition of a little common salt.

Filtration is the final process required to render water sanitarily pure, and to make it agreeable to taste, sight and smell. It should be carried out for all waters except those derived from deep wells and boreholes, and, especially, for surface supplies, as they are the most liable to contamination. Unfortunately, it involves further expense in capital cost and working expenses, so that a small town may not be able at first to afford it, but the supply works should be laid out originally so that filters may be installed subsequently when that becomes practicable. Filtration should succeed the other processes of purification, as they will assist it, so that space for their works should also then be provided. Good filtration removes pathogenic bacteria, objectionable odour, colour, turbidity, flavours and certain chemical impurities, and thus permits of the use of a less perfect water supply than would otherwise be advisable. The better originally is the water, the cheaper and more safe will be its purification treatment, and, therefore, extra expense is justified in going some distance for a good source of supply, rather than adopting a nearer inferior one.

There are three types of filter :—(i) Slow sand, (ii) intermittent, and (iii) mechanical. Slow sand filters are usually constructed in rectangular compartments about 200 feet by 200 feet, and may if they are uncovered have sloping sides. Covered filters require vertical walls, and as they are the superior of the two forms, it is better to build even an open filter with side walls so that, if necessary, it can be covered thereafter: the cost of covering is about one-third that of the complete filter. In slow sand filters the filtering sand is supported by coarse sand and layers of gravel, graduated from fine to coarse, of minimum thickness to prevent material being carried away by the underlying drains: these lower layers have no sensible effect in purifying the water, and act only as a support to the surface ones on which the action of filtration depends. The water, after passing through the sand, is collected by a main drain running axially down the centre of the bed, and this is fed by short lateral drains, eight to twelve feet apart, and all are laid with open joints at intervals. A better, but more expensive, arrangement is to pave the whole floor with bricks laid with open joints so as to form a continuous series of drains in order to secure uniform and slow moving drainage which will not disturb the upper sand. Slow sand filters are the most efficient type and are the simplest to work: they are best adapted to dealing with comparatively clear water: they are regular in action, remove most of the bacteria and effect a little chemical purification.

Intermittent filters are also constructed in rectangular compartments in which sand is laid and from which the effluent is drained. Instead, however, of filtration being continuous, it is intermittent; the beds are drained dry once a day, are allowed to aerate, and are then again filled and filtration is resumed; thus the amount of water filtered is reduced by the time the filters are dry. The aeration leads to a greater reduction of bacteria than does the continuous system, but the working of the intermittent one is slower, more difficult and irregular than that, and this type is therefore not often installed.

Mechanical filters are adopted extensively in America, where several designs have been patented. The body of the filter consists of a cylindrical wooden or steel tank, in which from two to four feet of filtering sand is placed on a layer of gravel. Water is admitted to the surface of the sand through a central vertical pipe, and after descending through the sand, enters collecting pipes at the base and is passed out for consumption. It is first treated in a coagulating basin, where most of the purification takes place. The rate of filtration is extremely rapid, and it would seem that the filter acts chiefly in straining off the bacteria in the scum formed on top of the sand. That thus gets rapidly clogged, and has usually to be cleansed once a day, by forcing water upwards through the sand for about a quarter of an hour, and discharging it over the top of the tank. The advantages are the reduction in the area and cost of the installation, the cleanliness of operation, and the removal of nearly all turbidity and bacteria. The disadvantages are the increased cost of working, the necessity for careful regulation of the coagulant by skilled operators, the large consumption of water run to waste in cleansing, and the difficulty of maintaining the bacterial surface film. The type is best adapted to turbid water not highly polluted, and least suitable for clear water much contaminated.

The location of the filters may either be near the source of supply, or in, or close to, the town served: after the water has passed through them, it must of course be absolutely preserved from contamination. The former location may be adopted when the water is thence conveyed in a watertight conduit or main, but is inadmissible when the duct is an open channel. It may secure more adaptable ground levels and cleaner surroundings, and it may lead to the removal of dissolved or suspended matter which might cause the corrosion, or blocking, of the supply main from it. The latter location will have the advantages of being under better supervision and effecting economy in pumping charges when the supply has to be raised to the town, and is the only one sanitarily permissible when the supply duct is an open channel.

Sand is used in all forms of filter and was first employed as a strainer: it removes turbidity, but by itself has no effect in this respect on germs, as these can easily pass through its interstices, however small; nor by itself does it cause much chemical purification, except a little simple oxidation of organic matter, during the short time the water takes in passing through it. The explanation of the efficiency of sand in filtration is as follows. When water which is slightly turbid and contains bacteria reaches a filter, a deposit, or skin, of organic germs entangled in the products of the cells themselves, vegetable *débris*, and inorganic matter, is gradually formed on the surface of the sand. It is this skin which greatly leads to the bacteriological purification of the supply, for in it the pathogenic germs are consumed by other living organisms. As filtration proceeds, this skin gets thicker and more impervious, thus reducing the rate of percolation until eventually it will stop it. Below the skin for some depth the individual grains of sand get covered with a glutinous coating of organic origin in which the different germs that pass through the skin are caught and mutually destroy each other: the sand has to be of some depth (usually about three feet) to let this action fully develop. It is not known whether the skin or the coating is the more efficient, but it has been ascertained that both are necessary to ensure bacteriological purity: as they get thicker, their purifying effect becomes greater. In England the vertical rate of filtration usually varies from eight to twelve feet a day (2.6 to 3.9 million gallons per acre) through the filter: the London rate is from two and a quarter to four inches per hour. The slower the rate, the more efficient is the filtration; the better the natural water, the greater is the rate of filtration permissible. Every precaution must be taken not to rupture the skin, as purification depends on its perfect continuity: one of these is to fill the filter from below with filtered water at a slow rate not exceeding four inches in depth per hour. As the sand gets clogged, its surface is scraped to lessen the thickness of the skin, until it is reduced to a minimum of one foot, or better, two feet, after which the bed has to be re-made. The sand should at first be quite clean and free from impurities: it is then called " raw." After, it has been scraped off and washed, it is known as " ripe," and this variety should be used in preference to fresh sand, as its grains have a small amount of coating and thus start bacteriological purification earlier.

CHAPTER XLI.

SUPPLY LINES.

A WATER-SUPPLY project consists of works for the collection, conveyance, purification, and distribution of water. The parts of a project may comprise :—

The headworks (reservoir, or intake) ;
The supply conduit, aqueduct or main ;
The purification works ;
The pumping station for non-gravitation schemes ;
The distribution system (service reservoirs, etc., and pipe reticulation).

The different kinds of schemes arranged in order of merit are—(1) Gravitation, (2) pumping to service reservoirs, (3) pumping to elevated tanks or stand-pipes, and (4) direct pumping. The advantages of gravitation schemes are that they are the safest, most economical in operation (although sometimes dearest in construction), and least liable to deterioration. When comparing different alternative projects the following should be taken into account—(1) Sufficiency of the supply and practicability of future enlargement ; (2) quality of the supply, both present and future ; (3) safety or reliability of the works ; (4) economy of supply ; (5) convenience and easiness of supervision ; and (6) the financial capacity of the town. The cheapest project is one supplying naturally pure water (such as from deep-seated springs) at a high elevation and near the town. The dearest is one where the source of supply is distant from the town, is at a low elevation with respect to it, and requires expensive purification. The headworks and purification works have been discussed in Chapters XXXVIII. to XL. : the pumping station and distribution will be dealt with in Chapter XLII., so that this chapter will be confined to the supply line.

Large towns can afford the expense of a long supply line due to distant earthworks ; small ones cannot bear this, and therefore the storage, or intake, for them will have to be arranged for in their neighbourhood. Thus, for them the choice of sites for reservoirs will be limited, and the rate of storage will probably be high compared with that for an irrigation work, which will be constructed at the best site available for the dam, etc., and one having cheap communication with the irrigated area. Still, as the quantity of water required for the supply of a town is comparatively small, and as distribution, etc., works are costly, the increase in the cost of storage may not be a large percentage of the expenditure required for the whole scheme. The supply line forms the communication between the source of supply and the works at the head of the town distribution system. Its length will probably be greatest when such source is a storage reservoir giving supply by gravitation, and least when that is a river from which the water will be pumped. It must be constructed securely, and at its downstream end, or along its course, must be minor storage works to tide over interruptions in its flow, either by accident or by maintenance operations. Its discharging capacity must be somewhat in excess of the average daily consumption rate, so as to be able to meet extra demands, such as will occur after it has been temporarily stopped. It should be capable of cheap enlargement to meet increased consumption in the future, and if originally of an inferior type, should be convertible into a superior one without much loss by reconstruction when such change becomes necessary. Supply lines are of two main descriptions—those flowing with free surface (open channels and masonry aqueducts), and those flowing under pressure (mains of different materials). The alignment of the supply line has to be in accordance with its nature, but consistent with this, should be as short as possible so as to lessen the time of transit and the cost of construction. If a superior form is under contemplation when funds permit of its substitution, the alignment of the inferior form should be modified, as far as practicable, so as to work in with that suitable for the superior one, especially at cross-drainage works.

An open channel for a waterworks is much the same as one for an irrigation scheme. The gradient should be as steep as the soils will stand with respect to the consequent velocity. Heavy embankments, deep cuttings and porous formations should be avoided, and land drainage excluded by double banks. Cross-drainages should not be allowed to enter, and works for passing their discharge should, if possible, be designed for utilisation by a superior form of supply main when that becomes practicable. Escapes for passing off internal flood water should be provided.

The advantages of an open channel are—(1) Its cheapness (this is the principal point in its favour) ; (2) its large discharging capacity capable of being cheaply increased; (3) its permanence; and (4) its small loss of head. The disadvantages are—(1) Its liability to sanitary pollution (this is its chief defect) ; (2) its tendency to contamination by marginal plant growth ; (3) its long length ; (4) its great loss in transit; and (5) its large cost of ordinary maintenance. The disadvantages generally outweigh the advantages, and it is therefore seldom adopted, and then, ordinarily, for a small scheme where every economy has to be practised. If constructed, a tail reservoir of some capacity should be provided, partly to allow time for silt clearances and repairs, but, chiefly, to let the water be improved in quality by lengthy sedimentation.

Masonry aqueducts are sanitarily superior to open channels as they are protected from external contamination. They are best adapted for schemes which have to furnish large supplies and to country with gentle slopes. When the cross-sectional area exceeds ten square feet, an aqueduct will probably be cheaper than a pipe main, but is likely to be dearer than that when of a smaller area : it is, therefore, generally unsuitable for a small scheme. To reduce the cost, the alignment should be as direct as possible ; the velocity should not be less than three feet a second, so as to prevent deposits and growths ; it may be as high as ten feet a second when good hard stone is used. For a small scheme, requiring the cheapest supply line practicable, a half-round glazed earthenware channel, or one of concrete formed *in situ*, might be used and might be left open, or slabbed over. Where more money is available, similar, but whole-round, pipes might be laid, or reinforced cement pipes made under the Hume patent might be adopted. High embankments and deep cuttings should be avoided, and the line should thus be nearly parallel to the surface of the natural ground. As in the case of open channels, cross-drainages should be excluded, and the aqueduct should be carried over them in troughs, or pipes. A large aqueduct is usually built of masonry in cut-and-cover with brick arching on top, and is covered three feet deep by earth filling, or embankment, to secure coolness or protection from frost. The advantages of a masonry aqueduct are—(1) Its sanitary suitability, (2) its durability and safety, (3) its cheapness for large supplies, (4) its cheap maintenance, and (5) its small loss of head. The disadvantages are—(1) Its cost and difficulty of construction for small supplies, and (2) its inability to withstand great internal pressure. For a small project, which can afford a better supply line than an open channel, it will generally be best to have a pipe main rather than a masonry aqueduct.

Pipe mains are usually of cast iron, riveted steel or wooden staves: other forms, already mentioned, are of glazed earthenware (the objection to which are the numerous joints), of concrete formed *in situ* (moulded on movable cores), or of reinforced concrete. Cast iron, on account of its nature and thickness, is the most durable and is cheap, but is also heavy and costly to transport and liable to breakage. Riveted steel is more likely to be corroded, is somewhat dearer, but is light, and as small sizes can be nested in large ones, is cheap to transport: it is difficult to make it into special forms, and owing to the internal roughness of its riveting, its discharging capacity is only 85 per cent. of that of smooth cast iron pipes. Wooden pipes have to be made of long-grained and fairly flexible wood, which would probably be unsuitable to Indian conditions of weather, vegetable growth and the destructive white ant. For small schemes cast iron is generally the most suitable, and as pipes of it are now made in India, the cost of oversea transport may be obviated. The alignment should be as direct as possible. The pressure to be withstood should be low, and when it is high, should be reduced by equalising, balancing, or break-pressure reservoirs, or by regulating devices—all these divide the whole line into independent sections. The main should be laid as nearly parallel to the ground surface as practicable, and should have a minimum earth cover of three feet to protect it and keep the water cool. It is best that it should be laid with a continuous fall; otherwise, there should be an air valve at each summit, and a scouring valve at each depression: rises above the general hydraulic gradient should be avoided. The pipes must be securely founded and packed at the bed and sides. Cross-drainage works will usually be pipe aqueducts or inverted siphons. The advantages of a pipe main are—(1) Its sanitary excellence, (2) its safety, quick-laying and repair; (3) its resistance to high pressure, (4) its quick delivery with little loss in transit, and (5) its cheap ordinary maintenance. The disadvantages are—(1) Its heavy capital cost, (2) its comparatively short life, (3) its liability to be choked by incrustations, and (4) its comparatively large loss of head. The advantages so much outweigh the disadvantages, that for most schemes of ordinary size pipe mains are adopted.

CHAPTER XLII.

PUMPING AND DISTRIBUTION.

PUMPING schemes are inferior to gravitation ones as being more subject to breakdown, of lesser permanence and more costly in operation. The cost of pumping is so much greater than any other working expense, that its capitalised value should be taken into account when comparing the total cost of competing projects. Pumping becomes necessary when the supply is delivered at a town at a level below, or but slightly higher than, its own, and has to be raised for distribution purposes. The different systems of pumping are in order of merit—(*a*) To a large high-level service reservoir; (*b*) to a small elevated tank, or stand pipe; and (*c*) to the distribution mains direct. The advantages of a high-level service reservoir system are: (1) It enables distribution to take place by gravitation; (2) it allows the pumps to work at a uniform speed, under practically uniform head, and for as many hours as desired; (3) it gives time for petty repairs; and (4) may lessen the combined cost of reservoir and rising main by making possible the reduction of the diameter of the latter. The reservoir may, however, not be practicable on account of the levels or limited area of the ground. The advantages of a small elevated tank or of a stand pipe are—(1) They may be the only possible way of gaining the elevation required to enable the supply to gravitate to the distribution system; and (2) the storage of the former, although small, is sufficient to obviate sudden changes in the working speed of the pumping engines. The disadvantage is that sufficient time cannot be obtained by their adoption for effecting petty repairs to the plant. The advantages of direct pumping are—(1) It gives flexibility by allowing the pressure to be regulated in accordance with requirements; (2) it visibly shows the variation in the rate of consumption, and thus enables a check to be kept on waste; and (3) it lessens the capital cost by the omission of the service reservoir, tank or stand pipe. Its disadvantages are that it does not afford storage to allow time to effect repairs and to provide for fluctuations in consumption. Pumping plant has, however, now been so perfected that schemes with direct pumping are made quite reliable, and are being adopted in cases suitable to them.

The pumping station should usually be near the town, to enable it to receive superior supervision, and near the service reservoir, so as to diminish the length and cost of the rising main : it should be located at the highest level at which it can be fed by the supply line so as to reduce the amount of lift from it. If it has to raise the water to allow it to pass through the purification works, there should be for them a sufficient area with suitable levels and sanitary surroundings near it : if those works are supplied by gravitation, they should be placed where those conditions can be obtained near the supply line, but even then should generally be as close as practicable to the pumping station to concentrate supervision. The permanent parts of the pumping station which have a long life—the building, the chimney and the intake well—should be of ample size to allow for expansion of the whole waterworks : extra space is also desirable in the tropics to ensure comfort in working. The temporary parts—the machinery of all descriptions—should be of size sufficient only for the requirements of, say, the first ten years : when expansion becomes necessary, it would be met by additional installations of machinery located in the vacant area of the pumping station provided for the purpose. These temporary parts consist of—(1) the boilers, including everything for the production of steam ; (2) the engines, including everything for the utilisation of steam power ; and (3) the pumps, including everything for the raising of supply. It is necessary to have a set of pumping plant in reserve as a stand-by to be used during ordinary repairs, or when a breakdown occurs. In small works it is advisable to have only one full-power set for ordinary working, and not to sub-divide it into two plants of half-power with a third half-power set as a stand-by. The provision of a full-power set for working and a similar one as stand-by, will not cost much more to instal, and will furnish more power. The essentials for the whole plant are that it must be reliable, suitable, within the capacity of the staff to manage and to effect ordinary repairs, and economical in working. The waterworks engineer should be able to select the best type of the different plants offered to him, and should be qualified to understand all tests for it and to carry out himself ordinary tests from time to time. Beyond this it is advisable for him to rely upon the specialised knowledge of makers of the plant for its design, after giving them all the information they require as to its general character, its position and levels, the duty it has to develop, the supply it has to give and the conditions under which it has to work. He should call for tenders from makers of repute and include the whole plant therein, so that the selected firm may be responsible for the entire installation. That firm should design the chimney and the setting for the boiler, and should be bound to work and maintain the plant for a specified period.

The rising main connects the pumping station with the service reservoir; the shorter it is, the cheaper will it be. The larger the diameter of the main, the less will be the loss of head in pumping through it, and, consequently, the less will be the cost of pumping. That cost should be capitalised and added to the construction cost of the rising main, and the cheapest arrangement taking the effects of lift and diameter into account, should be selected. The discharging capacity of the rising main should suffice to provide for a day's consumption during the working shift of the pump. The rate of consumption from the service reservoir varies greatly, and its maximum, which the distribution mains must be able to give, may be three times the average rate throughout the day, and thus generally will be considerably greater than the pumping rate. The consequent saving in the diameter and cost of the rising main can thus be offset against the cost of the service reservoir.

A service reservoir is a temporary storage of water at the head of the distribution reticulation. In a gravitation system, it will be at the tail of the supply line, and in a pumping system at that of the rising main. This reservoir serves many purposes—(1) it furnishes the supply at the fluctuating rate required by consumption draw-off; (2) it allows the pumps to work under fairly steady conditions; (3) it permits filtration to proceed at a steady rate; (4) it supplies the distribution system at a fairly constant head; (5) it provides for meeting sudden abnormal demands, as in the case of a fire; (6) it cheapens the distribution reticulation by shortening the principal mains; (7) it renders distribution more elastic in working when there is more than one service reservoir; and (8) it gives time for the repair of the rising main and (if there is no stand-by) of the pumping plant. A small town will probably have only one service reservoir, and that should be located as centrally as possible in it, so as to give the most uniform and highest pressures: it should command the whole town, and in the case of a gravitation project, should, if possible, afford pressure for fire extinction. In a pumping project for a town with greatly differing levels, it may be economical to have two or more service reservoirs, at suitable levels to reduce the pumping charge for otherwise raising the whole supply to the highest level. The storage capacity of the reservoir should suffice to meet the fluctuating demands of consumption, to supply water for fire extinction and to give time for emergent repairs. The last is the controlling consideration, and for it the storage capacity should be equal to half a day's average consumption. Formerly, two or three days' supply was contained in the service reservoir: this not only greatly increased its cost but also allowed time for the filtered water in it to deteriorate bacteriologically. A service reservoir is generally built of masonry and in two compartments so that one can be thrown out of use when necessary for cleaning or repair: it should be furnished with all the valves necessary for supply and control, and there should be a by-pass main, so that, on emergency, the supply can pass direct to the town without entering the reservoir. A reservoir should be roofed—(1) to keep the stored water cool; (2) to maintain its masonry cool and thus obviate temperature cracks; (3) to exclude dust; (4) to stop the ingress of mosquitoes; and (5) to prevent the growth of vegetation. The best form of roofing consists of masonry vaulting carried by piers and covered with embankment at least two feet thick. It costs one-third of the whole expenditure on the reservoir, and may therefore have to be omitted at first, but should then be arranged for, so that it may be added when funds permit.

If there is not a site available for a service reservoir, either on account of deficient area or elevation, a water-tower, or a stand-pipe, may be substituted for it. The former is an expensive structure, and the latter is also somewhat costly: both increase pumping charges, as with them all the supply has to be raised to the maximum height. They are therefore generally omitted in England and in preference direct pumping is resorted to instead; they are not likely to be required for a small Indian town. A water-tower is an elevated service reservoir of the minimum size: that will usually give a storage equal to one hour's average consumption, and this is provided to equalise the working of the pumps so that they need not follow the momentary variation of the consumption. A stand-pipe is a column of water designed to give a constant head under which the pumps will work. It is much inferior to a water-tower as it has only a very small equalising effect on the fluctuations of consumption draw-off. It really acts as a cushion to the engines and a shock absorber to the distribution pipes ; the modern system is to substitute for it for these purposes wrought-iron air vessels near the pumps.

There are two main systems of supply—the intermittent and constant services. The former is now discontinued in England, and is not applicable to a small Indian town, as it necessitates the provision of cisterns to each house for the storage of a day's supply. In the constant service water is supplied throughout the day ; it is thus in continuous circulation and is fresh. There are three main systems of distribution—the dead end, gridiron and ring. The dead end system consists of a main with independent branches from it, all terminating in closed, or " dead ends." There are many objections to it, but it is the cheapest, and may therefore have at first to be installed : it can be developed into the second system by adding mains connecting the dead ends together. The gridiron system consists of a central axial main from which branches are taken off and these are crossed by, and connected with, other branches, more or less parallel to the central main. Its advantages are that—(1) every pipe can thus be supplied from all directions, which is of great utility when a fire has to be extinguished ; (2) stagnation of water anywhere is prevented ; and (3) the areas to be shut off when repairs are necessary can be made small. Its disadvantages are—(1) the circulation prevents the exact calculation of the sizes of the pipes ; (2) numerous valves are required ; and (3) with it there is difficulty in applying district meters. It is generally the best system to adopt. In the ring system there are two main branches, one from each side of the supply main from the reservoir, etc., which return to meet each other at the opposite side so as to enclose the district, of which each branch serves half. The main branches are also connected with each other by a girdiron of minor branches and cross branches. This system has the same advantages and disadvantages as the gridiron one, but is generally more expensive than it as the bulk of the supply has to travel a greater distance.

Distribution calculations should be made by means of a map of the town on which are shown its streets and contour levels and the proposed system of pipe reticulation, for which the principal mains should first be laid down and the branches added afterwards. The town should be divided into districts, and if the levels differ considerably, the districts should be arranged into zones having levels varying within pre-determined limits. The discharging capacity of every main should be estimated from the daily allowance per head and the number of the population served by it, and from the daily demands of the services to be supplied; that capacity should provide for the probable requirements of the first ten or twenty years. The map should be kept up to date and should show all pipe lines, valves, hydrants, etc. The discharge required for each pipe and its consequent diameter should be calculated[1] so that there is sufficient head at every point for giving supply quickly and, if necessary, for fire extinction purposes. The cost of the distribution system is usually the most expensive part of a waterworks project, and therefore it should be carefully planned so as to secure economy with efficiency. To enable this to be done the following rules should be borne in mind—

(1) A pipe carrying a certain quantity of water will cost less than double of a pipe carrying half that supply; therefore a maximum concentration is economical;

(2) The shorter the distance to which the bulk of the water is carried, the shorter will be the larger pipes, and therefore the less costly will be the distribution;

(3) The more direct the bulk of the water is delivered to a given point, the less is the friction head and the greater the remaining available pressure for the same size of pipe, which produces further economy.

The distribution system consists of cast-iron pipes which for a small scheme should not be less than three inches (better four inches) diameter, hydrants, air valves, scouring, reflux, relief and stop valves, and in India, distribution cisterns for street service.

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[1] "Practical Hydraulics" by Thomas Box, E. and F. N. Spon, gives simple instructions.

PART III. ROADS.

CHAPTER XLIII.

GENERAL CONSIDERATIONS.

THE rapid progress of civilisation in modern times may be said to be due primarily to the development of communications. Railways have made travel by land easy and quick, steamships have united distant countries by shortening the lengths of voyages and by increasing their safety and comfort, and very recently the conquest of the air promises still further to abridge distance. By these long-distance communications mankind has been brought into closer contact, mind has been enabled to act on mind in a manner previously impossible, and trade has been rendered practicable between countries previously separated by then impassably extensive space. Engineering in its broad aspect may thus be said to be the pioneer of modern progress, as is evidenced by the fact that the development of the former has always preceded and led to that of the latter.

These long-drawn-out lines of communication would not, however, suffice by themselves, except perhaps in the case of thickly populated and highly civilised communities, as they require for their complement the shorter lines of roads which serve to extend their utility to a large breadth of country. Roads were of course the original means of travel and traffic on land, and at first were adapted only to the leisurely movements of the period. On the advent of the railway affording greater speed and comfort, the use of them lessened, and the tendency was not to develop them, and, occasionally, to abandon them. Now time appears to be taking its revenge, for with the coming of the quick-moving motor, the railways are being threatened with formidable competition, and the development of roads is again progressing. A railway is a great civiliser, but by itself cannot much extend its influence, and therefore requires the help of the lateral communication afforded by roads. Moreover, a railway is very expensive to build and work, while a road can be constructed and maintained for a small fraction of its cost. Some new countries will therefore best be opened out first by the road, and as they develop, will afterwards be able to afford the railway.

One objection to a railway is that it concentrates the population along it, whereas a network of roads distributes the inhabitants more evenly over the country. Railways, steam and coal have changed certain previously agricultural into industrial countries, which has not been an unmixed benefit to them, although their wealth has thereby been greatly increased. Motor traffic on roads is, however, tending to alter the conditions, as transport by it is ousting short-distance traffic by the railway, and townships with local industries are being formed where the road service is good. As illustrative of what has been stated above, it may be said that in England the classification, improvement and extension of roads are being attended to (at a cost in 1921 of about £50,000,000) ; in America many of the shorter railway lines are being taken up as they are no longer paying their way ; in Australia, where half the population lives in a few overgrown coastal cities and the inland area has a scattered and small population, an endeavour is being made to open out the rural districts by a good system of roads. The proper development and construction of roads is thus a matter of national importance which is now being widely recognised : such evolution must take into consideration, as far as possible, the future, as well as the present, requirements of traffic.

Roads may be divided into two great classes—urban and district. The former require a superior form of surface, can pay for its extra cost, and can obtain the more skilled labour and supervision necessary for construction and maintenance. Of such forms may be mentioned asphalt, tar-bound (tar-sprayed, tar-macadamised and pitch-grouted), wood and concrete surfaces. Asphalt requires little tractive effort, forms a jointless, impervious, sanitary, and easily washed surface, deadens the noise of traffic, is free from dust, and in temperate climates is practically indestructible : in tropical climates it becomes soft and liable to be worn into corrugations by traffic, while its volatile constitutents are apt to evaporate and thus to cause its disintegration. Of tar-bound surfaces the macadamised variety is best suited for heavy traffic, but is expensive ; the others are cheaper and are sufficient for light traffic ; all varieties ordinarily suffer by softening under the prolonged heat of the tropics. The tar which binds them is of very variable nature and is distilled to toughen and temper it, so that it may not be too soft in summer nor too brittle in winter. The toughening is due to ridding the tar of volatile products, and chemists should discover what should be added to it, and what taken away, to make it consistently the same in hot and cold weather. A petroleum from Trinidad is recommended as the most satisfactory binding material yet discovered and to be well suited to a hot climate. Wood pavements are superior to the ones mentioned above in that they are less slippery, and thus cause less distress and damage to animals and possible danger to riders and drivers. Again, temperate climates have the advantage over tropical ones, and it is a matter for trial and experience to ascertain if wood pavements can successfully meet conditions in the East. A combined strip pavement consisting of hard, short-fibred Australian jarrah, and of soft, long-fibred red pine, has been laid to prevent slipperiness: it is said that its life is longer than that of pavements made entirely of either of these woods. A concrete pavement has not only a concrete foundation (which may be strengthened by metal reinforcement and then be reduced in thickness), but also a concrete surface. If this proves successful, it should be suitable to conditions in the tropics but its cost will be considerable. District roads will generally have water-bound macadamised surfaces, as they cannot afford the much more expensive ones noted above. In India most district roads will be of this type, so that it alone will be dealt with hereafter. Once more, tropical conditions are against this surface, as the prolonged fair weather, the intense heat of the hot weather, and the downpours of the monsoon are all prejudical to it, but can be met by careful construction and maintenance.

District roads may be classified as—through or main line roads, branch roads, and feeder roads. Through roads may be defined as ones of considerable length passing through more than one district, and having important towns as their termini. The alignment of a new through road should, as far as practicable, be suitable for a railway. As traffic develops, the time may come when it will have to be considered whether it is advisable to substitute a railway for the road, or to construct the former on an alignment more or less parallel to the latter. To enable the first decision to be taken, it is desirable that the cross-drainage works of the road should be adequate, or capable of modification with a small amount of reconstruction, to the requirements of the railway. If, however, it is determined that the railway should be independently constructed, the presence of the already existing road will be of assistance during its construction, and thereafter it will be of advantage to the country that the bulk of its traffic, railway and road-borne, should move between the same main points. A branch road is one which connects an important isolated town, or a divergent valley, with the general line of through traffic. If the branch is a long one, it may be possible that hereafter a railway will take its place, or run in its immediate neighbourhood, and the considerations just mentioned will apply. If, however, the branch is a short one, under modern conditions, it is not likely that such a railway will be constructed, but rather that motor traffic will be developed, and the road should therefore be aligned so that it may cheaply be improved, if necessary, for this. A feeder road is one subsidiary, not to a main line road, but to a railway, port, or other connection with long-distance communication. Unless a feeder road is of some length, or serves important interests, it is not likely afterwards to be replaced by a railway, but it may be required for motor traffic and should therefore be set out accordingly.

In respect of their construction, district roads in India are thus classified—

First class—raised, bridged, and metalled ;
Second-class—raised, bridged, but not metalled ;
Third class—neither raised nor bridged and not metalled, but sometimes with cross-drainage works over the more important or difficult streams.

The nature and importance of the traffic to be served will determine the class of road to be adopted. The general character—alignment, gradients, cross-drainage works, etc.—should be preserved throughout a road, but should be improved, usually by greater width and superior surface, in the neighbourhood of large towns, as thus it will benefit the heavier traffic and the larger number of those who there use it. It has to be remembered that the conditions most suitable for the road are opposed to those for the traffic. A somewhat tortuous alignment with steep gradients closely following the profile of the country will generally cost least, but will retard traffic and make it more expensive. A highly curved cross section will best preserve the surface from damage by rainfall, but will be inconvenient for traffic. A hard surface will make the road more permanent, but is likely to wear roughly, and thus to incommode traffic. It is therefore often necessary to compromise between these conflicting interests, and the compromise should, as far as practicable, be on the side of the traffic, as that deserves the most consideration. The road engineer must adapt his construction to the requirements of traffic, and not expect the latter to lower its standard to meet the conditions of an inferior roadway. The essential matters of construction for a good road are—(i) perfect drainage, (ii) solid but elastic foundations, and (iii) a compact, smooth, impervious and durable surface.

CHAPTER XLIV.

ROADS AND ROADWAYS.

THE general alignment of a new road should connect the principal intermediate and the terminal towns by the shortest and easiest route practicable, with due regard to intervening minor towns and villages. It should take into account (i) the most level and direct course possible ; (ii) the best crossings of waterways and ridges ; (iii) the nearness of quarries for materials ; (iv) the avoidance of costly, unsuitable and difficult land ; and (v) the selection of ground which will make construction cheap and sound. Where fairly large towns are a little off the direct route, it may be advisable to divert the alignment towards them, so as to obviate the necessity for long connecting branch roads to them, and thus to reduce to the minimum the total mileage of traffic when that is fully developed. The best alignment is one which consists of long straight lengths united by gentle curves, crosses few drainages and those at right angles, and avoids unnecessary rises and falls. It should suit through traffic in general and local traffic in particular : thus, as a rule, an arterial line should skirt, not traverse, an urban area where the two kinds of traffic would interfere with each other To reduce the total lift, saddles should be crossed at the lowest, and valleys at the highest points practicable. In ascending hill inclines, steep sidelong or precipitous ground should be kept off as much as possible, so far as the gradients beyond permit, in order to shorten the length of the expensive and dangerous part of the ascent.

The gradients of a road should be regulated by the nature of its traffic. A ruling gradient should be fixed and not exceeded, so that full loads may be transported without decrement anywhere throughout the whole length. The flatter the gradient, the better will it be for all classes of traffic, and for surface consolidation ; along hill inclines, whenever feasible, the general gradient should be flattened, even at the expense of a small increase of length. An absolutely level long stretch of road may introduce difficulties in drainage, to avoid which an imperceptibly gentle gradient should be substituted. A rising gradient increases the haulage effort necessary; a falling one diminishes such effort but, if excessive, will tend to produce undue acceleration which has to be resisted by brakes or by the draught animals. A gradient of 1 in 30 is gentle; one of 1 in 25 is fair; one of 1 in 20 is moderately steep; one of 1 in 15 is a hill incline; while one of 1 in 10 is excessively steep, and should be adopted only in special circumstances and for short lengths. Long gradients should be broken by flats, or gentler inclinations, and their tops and bottoms eased so as to reduce long-continued tax on draught animals. Steep gradients should be short, flat ones may be long. The least total rise between two points is secured when there are no falling gradients towards the higher of the two, as these have to be made good by additional ascents. Where heavy traffic is in one direction only, the flatter rises and the steeper descents should be in that direction. The crests of saddles should be cut down, and the troughs of valleys embanked as much as cost will allow so as to reduce the total amount of lift.

The curves of a road should be regulated by the nature of the traffic, being made easier when that is fast-moving than when it is of a slow character. Curves are undesirable in the direct interest of traffic and should therefore be avoided as much as can be done, but when necessitated by the nature of the ground, should be made regular and of as large curvature as possible. They are particularly undesirable on high embankments, near cross-roads and bridges, and on steep inclines; unfortunately, they have to be numerous on hilly sections. On steep gradients they should be flattened in longitudinal section and gently tilted up to the outer side in cross section, and the road slightly widened to assist traffic. For rapid traffic on flat lengths the least radius should be 150 feet; as the gradient increases the radius may be diminished to a minimum of 60 feet on hill inclines. For slow traffic the smallest radius may similarly vary from 100 to 60 feet. When the line of traffic is not parallel to the roadway, it is an indication that the curve is too abrupt and that it should be eased. " Hair-pin " curves, where the road doubles back on itself, are objectionable and should be permitted only on steep inclines traversing sharp ridges, where they are unavoidable. To prevent collisions it is best that a curve can be viewed from end to end, but when this cannot be arranged, the length in sight should be as long as possible. For this purpose, on the inner side of the curve, projecting slopes of cuttings should be dressed off, especially at the top, overhanging branches of trees trimmed and bushes removed, and the ends of the cuttings splayed away where the depth of excavation is small: heaps of road material should not be stacked where they will interrupt the view.

A good foundation for a road has to fulfil the following conditions—

(i) It must throughout be strong enough to resist, without crushing or permanent set, the pressure which may come on it.

(ii) It must be thick enough to distribute the pressure over such an area of its bed that that in its turn will neither be crushed nor suffer permanent set.

(iii) It should permit the thorough and early drainage of all surface percolation water.

(iv) It should be carefully adapted to the nature of the subsoil.

To prevent permanent set, a material must not be strained beyond its elastic limit. An elastic material is one that will bend without breaking, and on removal of the force acting on it. will return in a short time practically to its original position. A plastic material is one that does not break up under pressure, but on its removal does not come back, either soon or completely, to its original position. Thus road surfaces, such as of macadam and of stone sets, which have a certain amount of elasticity, require an elastic foundation to aid this recovery. Wood pavement, which is liable to crushing, and asphalt, which is plastic, need a solid support like that given by a concrete bed. When macadam is placed on a rigid bed and is subjected to pressure, it transmits this to the bed within a conical volume bounded by a radiating line sloping from about 60° to 70° from the point of contact, and the bed by reaction transmits a corresponding pressure to the surface. At the same time, as the metal is elastic, horizontal displacements due to both sets of forces are set up—inside the cones, away from their common axis, and outside the cones, towards that. Thus the stresses tend to expand the material without the cones, and to compress that within them, and in consequence it tends to break up. When, however, between the road surfacing and the rigid base there is a sufficient depth of elastic foundation material, the surface pressure is distributed over a wide area, and the external displacement gradually disappears in the body of the formation. As the internal stresses decrease from the road surface towards its bed, so should the nature of the supporting construction vary, the material nearer the surface being selected of a harder and more elastic variety than that below it. The character of the structural foundation should be adjusted to the amount of pressure it has to support, and should be stronger for heavy traffic and weaker for light traffic. It must also be adapted to the nature of the subsoil: when that is hard but resilient, the depth and width of the foundation may be less than they should be when that is rigid (*e.g.*, rocky), or is plastic (*e.g.*, clayey or swampy).

The width of the road surface must be in proportion to the amount of traffic to be carried by it ; the greater it can be made within ordinary limits, the better. Fair general allowances for it are for—First-class roads, 18 to 20 feet ; second-class roads, 16 feet ; and third-class roads, 12 feet. In addition to the central track it is advisable to have, on each side, side-widths from 3 to 6 feet wide coated with less expensive, but still fair, surfacing ; they should not be made of earth or soft material, as that will be muddy in wet weather, dusty in dry weather, and liable to be cut up throughout the year. The side-widths have the following advantages—

(i) They support the sides of the road metal proper, and prevent it from spreading.

(ii) They virtually increase the width of the roadway, and will allow that of the central track to be diminished if necessary.

(iii) They permit the central track to be surfaced and consolidated in one operation, which will make a better roadway than if this were done separately in two half-widths.

(iv) They form softer and thus more convenient tracks for light traffic—riders on horses or cycles and foot-passengers.

The road surface should be as impervious as possible, so that excessive percolation may not find its way into the sub-surface, the embankment and the natural foundation, if these will thereby be rendered soft. A certain amount of dampness is desirable so that the blindage may retain its binding effect; an excess amount of it is prejudical to the life of the road, and where the roadway is subjected to long-continued rain, the surface should be exposed as much as possible to the drying action of sun and wind. A road must be thoroughly consolidated so that it may withstand abrasion, not only on its surface, but also in the interior of the metalling. In a loosely compacted and badly cemented road there is so much play among the particles of metal that they soon become rounded by wear, and thus still less capable of withstanding attrition by traffic. An insufficiently consolidated road may have from 15 to 20 per cent., and a thoroughly consolidated one, 10 per cent. of voids: excessive abrasion may reduce the macadam by 40 per cent., pulverising part of it to fine dust, the excess of which, after filling voids, will come to the surface. The surface must be durable and smooth to facilitate the passage of traffic and to ensure evenness of wear. The object to be aimed at is to secure a mosaic-like surface formed by the close interlocking of the particles of metal, to obtain which there should be the minimum of cementing material, as the condition of that is so liable to change. A dusty, rutty, or nubbly road is an indication of the coating being too old; of inferior or unsuitable metal having been used; of too early application of blindage; of want of proper consolidation; or, if soft material such as laterite has been used, of its too early consolidation in the rainy season and its subsequent churning up. Too thick a coating makes a road hard and unyielding, too thin a one will not resist traffic properly: the thickness should therefore be adjusted to the nature and amount of the traffic. On a new road a first coating of metal should be laid on the prepared foundation in two layers, each, say, 2½ inches thick at the sides and 4 inches at the crown, another specification prescribes 4 inches for the first layer and 2 inches for the second, placed uniformly over the whole width on a 6-inch foundation; another, a uniform thickness of 9 inches for important roads with heavy traffic.

CHAPTER XLV.

SURFACE AND DRAINAGE.

CAMBER, or barrel, is the name given to the cross-sectional profile of the road surface. It is required solely for the purposes of drainage of the road surface and its curvature should therefore be marked for soft, permeable material, and nearly flat for that which is hard and impervious. It is not wanted in respect of the traffic, for that is best served by a perfectly plane surface which allows the wheels on each side to bear evenly and for their full width on the roadway. A curved inclination of the surface makes the wheels bear unevenly on it, thus causing them to shear and cut into it; if the curvature slope varies from point to point on the section it tends to set up a cross-strain on vehicles; and if it is excessive, is likely to cause side-slip to quick-moving traffic. As a compromise between these two conflicting interests, the smallest amount of camber which will shed the rainfall with sufficient quickness should be allowed. A flat camber distributes the traffic more evenly over the width of the road than does a highly curved one, but is more liable to the formation of depressions and to shear towards the sides. The wider, less permeable, less sheltered and more important the road and the faster the traffic, the less should be the camber. In regard to the shedding of the rainfall, the inclination of the camber should decrease from the crown of the road to its sides, for as the volume of water to be discharged thus increases, it requires flatter and flatter slopes so as to maintain, but not to accelerate, its velocity.

There are three main types of camber—the convex, the concave, and the sloped. The convex camber is the form almost universally adopted: it is usually a portion of a flat circular curve so that the curvature slope increases regularly from the centre to the sides where it is more or less pronounced. This variation is not only unnecessary for rain-shedding but also tends to concentrate traffic on the flat crown. In favour of this camber it is sometimes urged that it acts like an arch, but this is not the case, owing to the smallness of the curvature, the irregular character of the roadway material, and the nature of the abutments. The concave camber has the curvature of the road reversed from that of the convex one, that is, it inclines in regular curves from the sides downwards to the centre, which therefore becomes a trough. Its design thus sheds the rainfall correctly *as just explained. On the other hand, although it has a few* advantages from the point of view of the traffic, it has many more disadvantages in respect to it, and is therefore seldom constructed. It is more adapted to urban than to rural districts. The sloped camber has a very gently curved crown, a few feet wide, and from it on each side, the surface has a plane uniform slope—one-half inch, or less, to the foot—to the edge of the road. It has the following advantages—

(i) It obviates the excess velocity of the drainage at the sides, and thus diminishes the tendency to guttering at the edges.

(ii) It is simple to set out and construct.

(iii) It provides for an increased thickness of metalling at the centre where the traffic is heaviest.

(iv) It allows the wheels to bear evenly for their full width on the surface.

(v) It does not produce any cross-strain on vehicles.

It thus fulfils the requirements both of rain-shedding and traffic: it is apparently the best form and should be more extensively adopted. A development of this type is of particular use on hill inclines, when the whole road surface is made with a gentle cross slope from the precipice side down to the hill side: this prevents drainage guttering down the precipice slope and deflects both it and out-of-hand traffic safely to the hill side.

Metal for roads should be hard, tough, dense, impermeable, weather-resisting, good-binding, resistant to attrition and pounding, of uniform character and suitable to the nature of the traffic; as a rule, fine-grained and heavy stone furnishes the most suitable metal. The cost of metal depends chiefly upon that of its preparation and carriage; the former being nearly the same for different kinds of stone, the latter, which depends upon the lead, is the chief variant, and sometimes determines the selection of the variety to be utilised. The principal consideration should, however, be the quality of the stone, which limits its life, and that should be ascertained by tests. The laboratory tests are microscopic examination and the attrition of the material when wet, for little is worn off when it is dry. These tests give only qualitative, not quantitative, results, and the latter does not reproduce all conditions which occur in practice. They should, therefore, be combined with the actual out-of-door test of the behaviour of the metal when laid on the roadway : this last is practically the only one taken into account in India. For it careful records should be maintained of the life and metal from different sources, how this was affected by situation and treatment, what maintenance cost was incurred, and how traffic was served. A quarry that produces poor results should be permanently abandoned, and metal should be procured only from such as supply the best material obtainable. The size of the metal should vary with the nature of the stone and the character of the traffic : large particles are difficult to consolidate, require a good deal of blindage, and form a rough road. The smaller the particles, the smoother the road, but the shorter its life : the harder the metal, the smaller should be the particles. Where consolidation is difficult, as on hill inclines, small-sized metal is desirable : where it is easy, as when steam rollers are employed, the metal may be larger : the usual limits fixed are that the particles should pass through rings varying from 2½ to 1½ inches in diameter. The metal should be nearly cubical in shape, so as to make it bind well and so as to diminish internal attrition ; round, or oblong, pebbles and angular chips, or flakes, should not be used. Hand-broken metal is superior to machine-broken, as the latter is apt to be flaky and to have internal fractures.

Blindage materials are what are required for finishing off the metalled surface and side-widths. Gravel should be fine and clean and have a little clayey matter to make it bind. Muram (disintegrated trap rock) should be sound, hard, binding, clean and resistant to the weather. Sand should be sharp, hard, gritty, and clean (that is free from earth), and should not have soft nodules nor large particles. All road materials should be prepared up to specification at the sites whence they are obtained, and nothing should be brought on to the roadside which cannot be used as it is. It is advisable to stack all road metal and blindage on levelled and numbered stacking platforms at intervals of, say, half a furlong, and in the quantity required for the interval. This system will reduce the work of measurement ; facilitate check ; give full measurement and proper distribution of material ; preserve the cleanness of the material and prevent its waste during spreading ; and be convenient and safe for traffic.

Consolidation of the road surface is necessary to ensure—

(i) Facility of traffic, by the formation of a smooth, regular, clean and hard track;

(ii) Solidity of the road metal, thus lessening internal attrition;

(iii) Impermeability, whereby the rainfall is shed rapidly and not allowed to penetrate the road freely.

To secure these advantages the sub-bed of the metal should also be consolidated to a regular profile so as adequately to support the actual wearing surface, and to prevent its suffering by settlement or displacement of its foundation. Immediately below the metal should be a layer of gravel or muram, which during consolidation will be forced into its bottom interstices and thus will hold the particles together. Rolling should be gentle at first and be carried out by light rollers, so as to avoid corrugating the original loose surface: it should be completed by heavy rollers until they cannot further compress the surface nor bring the particles closer together. Thereafter, blindage should be applied and well rolled in. Rolling should be commenced at the sides, so as to keep the metal there in place, and should be continued uniformly to the centre: it should be carried out early in the rainy season if the metal is hard, and late if that is soft.

Good drainage is essential for prolonging the life of a road. The surface should be accordingly formed as just described. Its foundation should be of durable, self-draining material, so that it may pass away the percolation water that comes to it. Good side gutters are required to carry off at once all surface water and internal percolation, and for this purpose should be deeper in retentive than in porous soils. Where the ground is soft and liable to hold water, or there are springs, cross-drains, or hard dry material, may have to be laid under the roadway, and should be graded with a small downwards inclination from its centre line to its sides, and discharge into gutters. The object of these arrangements is to secure a dry foundation, for a wet one by capillarity may cause the whole formation to become moist and yielding, and the surface to deteriorate more rapidly than it will do by any other factor of wear. Gutters are not required where the road is in bank over a foot high: there the drainage should pass over the ground as a thin film, and not as a concentrated discharge. Gutters, when necessary, should be vee-shaped in cross section, sloping say one in three downwards from the road, so that vehicles leaving that can rejoin it easily, and so that drainage may be diverted away from, and not directed to, the formation of the road. Gutters should be led away from the road at the crests and bases of steep gradients, so as to lessen the discharge, and thus prevent erosion downstream of the diversions. Long gutters should be diverted at intervals so as to discharge over the fields at places where they will not do harm, or into parallel and external drains (which alone should carry large volumes), or into natural drainage lines. Where the bed of a gutter or drain is likely to be scoured, this should be prevented by the construction across it of curtain walls of dry rubble, boulders etc., the tops of which should slope gently down from the road. Catchwater drains should be excavated—where much land drainage has to be intercepted; where the discharge of long gutters is diverted away from them at intervals; or where subsoil water has to be drained from the road foundation. They should be aligned some distance from the road; should contain their high-flood discharge; should not breach nor spill against the road bank; should be led tangentially into natural cross-drainages; and should have clear outfalls.

CHAPTER XLVI.

CROSS-DRAINAGE WORKS.

THE high-flood discharging capacity of catchments was discussed in Chapter XIII. with respect to irrigation works: the same considerations in regard to them apply to the provision necessary for the cross-drainage works of roads. Although the failure of the latter may not be accompanied by loss of life and property, as is possible in the case of the former, still it will be attended by structural damage and much inconvenience to those who make use of the road. If to avoid such failure an unduly large provision for flood discharge has been made, excess expenditure will have been incurred on both classes of works, but the excess may be proportionately less on cross-drainages than on storage reservoirs. For the first-named the increased provision will usually be made either by enlarging the spans of the work or by adding to their number: the effect of this will probably be to bring the expensive abutments and wings on to higher ground, and thus to reduce their cost. As roads facilitate inspection, it is easier to conduct flood observation for them than it is for out-of-the-way irrigation works: as many of those observations as possible should therefore be made on constructed roads, so as to gain information about flood discharges, and this will be of great use for designing works for new roads. The record of the afflux and tail levels of extreme floods should be permanently engraved on large cross-drainage works.

When calculating the flood provision necessary, the actual conditions of a stream must be considered. If its course is tortuous its velocity will be less than that due to its bed slope, as it will be reduced by eddies and other irregularities of flow. If the cross-drainage work is situated at a sharp bend, it will accentuate these irregularities, and, in particular, may lead to increased scour on the concave side of the curve. If at the crossing the flow is oblique to the alignment of the road, a work with piers at right angles to that alignment will obstruct the flow, and one with piers parallel to the flow (involving skew arches) will introduce difficulty in construction. For these reasons it is desirable, when practicable, to cross the stream at right angles, where it has a straight and uniform reach, both upstream and downstream, extending, say, for distances, respectively, ten and twenty times its width for a small quick stream, and for half those times for a large slow stream. A tortuous channel may often be straightened by excavation, and the excavated material used for the construction of the road approaches. The beds and sides should, anyhow, have removed from them all projections which would otherwise retard velocity. A stream may carry down boulders, stones, gravel and silt, which may be stopped by the cross-drainage work and lessen its waterway—a regular course and a large depth of flow will tend to prevent this. Again, trees and bushes may be borne along by the flood, and if entangled by the work, might lead to its destruction by damming up the stream—large spans and considerable clear headway are the remedies for this. When a road runs along a principal valley, it may have to cross tributary streams near their confluence with the main one. During floods the latter may dam up the former and the cross-drainage design must take this into account, by treating the spans as partly submerged orifices and raising them accordingly. It is, however, far better, when practicable, to align the road above the influence of the high flood of a main stream. If a stream has low or undefined banks, it may breach them during floods and tend to cut away the approaches of the cross-drainage—to prevent this the longitudinal and cross sections of the stream should be improved as much as possible, and the road embankment should be securely founded, formed, consolidated and pitched on the upstream side. As a general rule it is not advisable to design a cross-drainage work so that it will appreciably raise the natural high-flood level of a stream, as thus riparian property may be damaged, the foundations may be subjected to increased scour, and the road approaches to greater pressure and infiltration. Certain streams may be liable to abnormal floods due to natural cyclones or to the breaching of reservoirs, which will thus act as artificial cyclones. To make permanent provision for this in the design of road works crossing them might, however, cause greatly increased expense. In such a case, the top of the embankments leading to an important bridge should have a gentle gradient rising to the bridge, and extending from a level "breaching section," say, three feet above normal high-flood level, which will come into action only during such abnormal floods, and will thus save the bridge from being overtopped thereby. The breaching section should be as long as possible, and should be located some little distance from the bridge, where the embankment is low and the natural ground hard and level, so as to prevent the formation of a deep scour channel should it come into flow. This temporary provision will entail little expense in remaking the embankment should a breach occur, and will not add unnecessarily to the original cost of the road should the abnormal flood not happen.

The location of cross-drainage works is frequently determined by the desire to preserve the general alignment of the road as straight as possible. For important works this consideration in the interest of traffic has to give way to the necessity for securing good sites for them ; for less important ones small deviations from the general alignment are permissible as such will not much increase the length of the road, and will also diminish the monotony of prolonged straights. The foundations of cross-drainage works should be made quite secure ; rock is best for them, but where this does not exist, the foundations should be carried deep, and in inferior soils should be protected by inverts and curtain walls upstream and downstream. To diminish the cost of the abutments and wing walls and to avoid high embankments, the road alignment should, if possible, meet cross-drainages where the stream banks are hard and high. The road approaches to these works should be straight for as long lengths as possible, and sharp curves should be avoided. A register should be maintained of all cross-drainage and other works on a road. In it should be tabulated descriptions of the works ; their consecutive numbers ; their mileage ; the numbers, spans and nature of their vents ; the heights of springing, etc., above bed ; the rise and thickness of arches, etc. ; the thickness of the piers ; descriptions of the abutments, and wings, etc. ; the positions and reduced levels of benchmarks on them ; and a record of high-flood levels.

Bridges for district roads may be timber-topped, iron-topped, or may have masonry arches. Timber-topped bridges are cheap for pioneer roads through wooded areas : otherwise, they should be avoided as they have a short life, being liable to rapid decay in the tropics, and may be destroyed by fire. Iron-topped bridges can be constructed of longer spans, and thus with fewer piers than is usual in the case of arched structures. They give more headway to drift timber, and more waterway, owing to their narrower and less numerous piers. They are, however, liable to rust and therefore require painting which adds to the cost of maintenance; near the sea coast rusting takes place quickly, and there it would be better to case the ironwork in concrete, or substitute reinforced concrete for it. Masonry bridges look best, especially if constructed of stone, not brick, are most permanent and cost least to maintain. Their arches are generally built of stone, or brick, but reinforced concrete has recently been substituted for these; to give a good effect the arch rings should project three-quarters of an inch from the general face and the keystones another three-quarters of an inch. The junction with the road embankment may be made either by splayed wings or returned walls: the former protect the toes of the approach embankments from the rush of flood water; the latter do not, so that when they are adopted, the ends of the embankments at them have to be pitched. Returned walls act as counterforts supporting the abutments, and may reduce the amount of reconstruction necessary should a moderate increase of flood waterway be required in the future: their parapet walls afford greater safety to traffic which is useful when the approach banks are high. Wing walls are the best form when the stream crossed has a high flood velocity, and returned walls when it has a low one.

Culverts are small arched structures which are suitable for crossing small streams that have defined and moderately high banks. As they pass under the road embankment and are not easily visible from its surface, they do not affect nervous animals crossing them. Slab drains are adapted only to small streams, and, especially, to those with undefined banks; the great objection to them is the narrowness of their spans, leading to silting, but these may be increased a foot by corbelling out the tops of the piers, etc.

The works just mentioned are permanent ones and should therefore be constructed for high-class roads, the character of which is not likely to be improved. For lower-class roads where economy is essential, stream crossings may be substituted for them. The cheapest form is a level crossing, or dip, in which the roadway is led down each bank at a gradient, usually not exceeding one in twenty, and across the stream, with a level, unbarrelled surface, and if possible, at right angles to it. The next higher type is a road dam, or "Irish bridge," for which two parallel curtain walls are constructed across the stream bed and continued for a short distance as flanks up the approaches; between them is the roadway : the downstream wall should be securely founded. A road dam is superior to a level crossing as it diminishes the height of ascent for the traffic, and is preferable to that where the stream bed is rocky and irregular. Another type of road dam consists of a rubble mound, with paved top, carried across the stream. The highest and most permanent form of stream crossing is a submergible bridge, or a rubble mound causeway pierced with vents, or a combination of the two. This form passes small floods under it, but large ones flow over it (when it virtually becomes a siphon), and the structure is designed to withstand their action. It effects great economy in construction in districts traversed by numerous large torrents that have heavy floods at intervals during the rainy season, and a moderate flow between these, but are practically dry during the fair weather. The inconvenience of the road becoming impassable during large floods is but slight, as then traffic is, anyhow, suspended owing to the intense rainfall which produces them. On the other hand, the great benefit of bridge crossings is thus secured for most of the rainy season, and during the whole of the fair season. If there is not a natural pool below the site of such a causeway, it is desirable, if practicable, to make an artificial one, or water cushion, by constructing a little downstream a raised bar across the stream to protect the toe of the rubble mound of the crossing.

PART IV. BUILDINGS.

CHAPTER XLVII.

ENGINEERS AND ARCHITECTURE.

SOME engineers are inclined to disregard architectural considerations in respect to their structures, as not being connected with their profession, and to attach importance only to purely utilitarian ones. Others are content to follow standard designs rather than to impress their own individuality on them, thus debasing art to manufacture, for individuality is vital to art. A few with artistic cravings endeavour to beautify their buildings but for want of guidance fail in their attempts. A smaller number, possessing not only architectural instincts but also acquired skill, design their works so as to satisfy both æsthetic and structural requirements. To the last named it is unnecessary to give advice, but to the others perhaps a few simple hints may be offered so that their constructions may not incur the reproach usually attached to buildings erected by a public department. To succeed in producing good structures the designer should have a love for his work, and a knowledge of how the best effects can properly be obtained.

Buildings should indicate their purpose and should not assume forms out of keeping therewith, nor be out of harmony with their surroundings. They should be designed so as to obtain convenience and comfort and to meet climatic and structural demands. A good plan is the essence of architectural design and it should be emphasised by the elevation, so that both should be studied together. Proportion, not ornament, is the basis of architecture and should be secured by ordered variation of the parts : the principal features should be advanced and the minor ones retired so as to gain pleasing variety and so as to escape dull uniformity. All art depends upon good craftsmanship, which is its supreme test and indicates high technical skill. Ornament should be sparingly used and should be restricted to bringing out the main features of the construction : it should not be applied lavishly nor merely to produce an effect ; it should bear a relation to the character and nature of the building. Colouring should be varied and tastefully applied so as to satisfy, or stimulate, the sub-conscious mind. Thus the engineer may well remember his artistic limitations, and that restraint will beautify his construction while profuseness will vulgarise it. At the same time he should avoid large uninteresting features in walls and roofs, and crude or inappropriate hues.

Style is called the grammar of architecture : still it is not essential to preserve the same style throughout as is proved by some of the large cathedrals of England which exhibit many types of architecture, but these are so skilfully blended as to create harmonious wholes. However, it is safer for the engineer to follow simplicity in this respect, and to adhere to a single style in each of his structures, or groups of structures, and one suitable to climatic conditions.

In regard to construction it should be remembered that buildings harmonise most with their surroundings if built of local materials : the builder can best show his capacity by utilising such materials and will thereby also effect economy. It is not true saving to use inferior materials and it is extravagant to select unduly expensive ones ; a proper middle course should be adopted. With verandahs enclosing the main building the walls of that need be only of good simple masonry. All shams should be avoided ; they are deceitful in intention but unsuccessful in realisation. A few of these often carried out are—painting corrugated iron roofs red to represent tiling, lining plastered surfaces to resemble block courses, false pointing to disguise the actual masonry, colouring brickwork to make it appear of superior quality, but depriving it of texture, etc. The materials employed should be treated in accordance with their nature—thus stone masonry should have simple mouldings, and the harder the stone, the plainer should these be ; brickwork may have smaller and more elaborate detail and be altered in laying and colouring ; even concrete can be modified in surface appearance to exhibit texture and varied hue.

In India verandahs form the main part of the visible externals of most buildings ; special care is therefore necessary to design them so as to be effective. First they should be treated as verandahs and not as the main building itself. By widening them where sitting-out space is desirable in residential buildings, and by narrowing them where they serve only as passages, variety may be given to the elevation and this may be increased by grouping the verandah openings in sets. On the sides exposed to the sun and prevailing wind the verandahs will naturally be open, but on the others they may be enclosed to form minor rooms used only for short periods, and this will result in considerable economy. The shaded recess behind the face of an open verandah has an æsthetic value which should not be destroyed by the entire boxing in of that face by trellis work or glazing.

Rooms should be planned to secure the greatest convenience to the occupants, and doors and windows spaced so as to admit light and air conveniently, and, when necessary, to give needful privacy. Each room should be considered a separate unit and should not be made dependent on its neighbours for light and ventilation unless these are *en suite*, as in the case of bedrooms, dressing rooms, etc. Light should be distributed and regulated as required, for glare adds much to the discomfort of occupants. Some reduction in the height of rooms is possible if due care is taken to get proper ventilation both at top and bottom so that a constant change of air may be obtained as this will promote coolness. The dimensions of rooms should be designed to suit their purpose and waste spaces should be avoided. To gain as much free floor space as practicable recesses should be formed in walls to take the larger articles of furniture, and the general floor plan arranged to suit the disposition of the others.

Economy should be practised as much as is feasible—by good planning; reduction of verandahs and the thickness of inner walls and partitions; diminishing somewhat the number of doors and windows and the quality and size of minor ones; avoidance of expensive roof trusses, and unnecessary details and ornamentation; and by the lessening of maintenance costs by sound construction. Thus money will be available for increased accommodation which is the chief requirement of the dwellers in a residence.

An architectural building gives satisfaction to the occupant, affords gratification to the beholder and confers reputation on the designer and constructor. Nature points the way to be followed—her compositions unite design and beauty obtained by simple means, and are adapted to their purpose.

CHAPTER XLVIII.

NOTES ON BUILDINGS.

THE main considerations which should govern the design of buildings were dealt with in the last chapter: a few additional ones are mentioned below. Engineers will chiefly be interested in the construction of public offices and public and private residential buildings for officials. In regard to the first named it is necessary to ascertain from the departmental officers concerned what are their requirements, the number of their staff, the nature of the accommodation immediately wanted, and what provision for future extensions should be made. For such offices probably type plans exist and will be worked to. As to these it may be remarked that, as the types were presumably settled after taking into account various constructed designs, so it is quite possible that with further actual experience improvement of them may be found desirable. It is best therefore to regard all type designs as not immutably fixed and from which no departure is permissible, but as general guides which, for good reason and under proper sanction, may be modified to suit altered conditions or to secure improvements. This will lead to the construction of buildings differing somewhat in design from each other, which will add to the stock of experience from actual practice, and thus afford opportunity for further betterment of design: it will also give the designers more interest in their work and more scope for their ingenuity.

A building should not only afford accommodation suitable in respect to size and disposition, but should also be adapted to the climate of the locality in which it is built. Now in the great area of India there are four principal climates, namely, those which characterise the hilly regions, the hot plains of the north, the more equable plains of the centre and south, and the coastal districts. A design which is suitable for one place may thus not be desirable for another, so that to prescribe a universal type is wrong. Naturally also, every climate has its seasonal variations which differ greatly from each other, and a fixed building cannot therefore meet all conditions equally well. The aspect chosen for it should be that which will be best in the most trying season, which in the East is generally the hot weather: the requirements of other seasons should be provided for by temporary additions or adjustable contrivances.

For residential buildings domestic comfort has to be studied and it is therefore usual and desirable to consult the first prospective occupier as to his wishes, for he may have useful suggestions to make. However, ideas differ and some are peculiar to an individual and not shared by others, so that the designer, while welcoming proposals, should use his judgment and experience and plan his building to suit the requirements of future tenants generally, especially as they are likely to occupy it longer than the officer consulted, who may indeed, owing to official changes, never reside in it. An Englishman's house is said to be his castle, that is, he desires to enjoy his residence by obtaining privacy, but this is often not fully attainable in the ordinary Indian bungalow, planned on barrack lines with all rooms open to view by casual visitors. Thus, following English precedent, the front door is usually placed in the centre of a single-storeyed bungalow. That position is selected for it in England to gain a symmetrical appearance and well-disposed arrangement of the rooms, and because, as a rule, on the ground floor there are only the public rooms, while the private bed-rooms are upstairs. A better situation in the bungalow will be to place the main entrance at one end of the building, so that the bed-rooms at the other end may be out of public view. Similarly, single-leaved doors in private rooms should be hung so as, when ajar, to disclose from the exterior as little of the interior as possible.

The plan determines the arrangement and sizes of the rooms, the elevation settles the appearance of the whole building; the two should therefore be designed with relation to each other. To aid making the former it is useful to cut out in paper pieces representing to scale the different rooms, and to shift these about until the best general plan is obtained. When fixing the size and shape of the individual rooms, the sizes and positions of the principal articles of furniture to be placed in them should also be plotted to scale on their plans. Single-storeyed buildings present a somewhat squat appearance with their large roof areas superimposed on low verandah walls. This effect can be partially improved by constructing separately the roofs of the main building and of the verandah with a narrow strip of walling between them, which might be pierced by clerestory windows. A double-storeyed building generally looks better than a single-storeyed one, and should preferably be designed to secure its many advantages: its disadvantages are connected with sanitary and water-supply arrangements when there are not public services for these.

Coolness of construction should be obtained in hot districts so far as comfort, permanence and safety will permit—the first was gained at the expense of the last two in the old type of Indian bungalow by its thick walls of sun-dried brick and roofs of thatch, or, when flat, of mud. It has been proposed to build walls hollow or with non-conducting coatings, both of which measures will be expensive: if the exterior walls are kept shaded, they will practically be as cool as it is possible to make them. For this purpose the walls of minor rooms occupied for short time can be protected from the sun by sunshades, or considerably projecting eaves, and those of major ones by verandahs, which themselves in very hot districts should be sheltered by continuous sunshades. For pitched roofs patent heat-resisting tiles have been made, but they usually look glaring when new and unsightly when weathered: ordinary tiling, with, however, large-sized tiles, will suffice for most districts as they enclose air spaces, and in very hot ones may be whitewashed, as this may lower the temperature by 10° F. or more. Flat roofs are being constructed in reinforced concrete, enclosing air space, which should be satisfactory. Of course the best protection against the sun for rooms occupied during day time is afforded by constructing an upper storey above them.

Ventilation is a matter of great importance in tropical areas, for not only is it required, as in temperate climates, to change air vitiated by respiration, but also to remove that which has become saturated by evaporation from the body: this removal will encourage further evaporation therefrom which will cool it. Practically little has been done structurally in India to secure proper ventilation, and dependence is still placed chiefly on the open door and window, or the punkah, when these have to be closed on account of the heat, or do not admit a current of air when there is no wind. The punkah is unsightly and cumbrous, darkens the room, and usually requires a puller to work it: it is, however, simple and effective in changing the air. An electric fan in the centre of a room simply causes the air to revolve and does not change it: inlet pressure and exit exhaust fans will induce currents of fresh air, but they are expensive to work in towns and generally impracticable in up-country districts. Ordinary ridge ventilation is out of control and may admit dust and rain. Upcast shafts have been recommended, as they automatically cause a moderate movement of the air when they are heated by the sun, or have lighting (and thus heating) arrangements under them. For district bungalows each main room might be thus ventilated by a sheet iron upcast shaft with an extracting revolving cowl at its top. The circulation of air can be promoted by open door and window heads, and openings through the walls below the ceilings, that will allow the vitiated air as it rises to escape at a high level.

Lighting should be arranged so that it is—(i) sufficient everywhere in the rooms; (ii) not excessive so as to produce glare; (iii) disposed as required; and (iv) under a certain amount of control or adjustment. Clerestory windows will admit light at the top as well as afford upper ventilation. Frosted glass in the bottom panes of windows and glazed doors will reduce glare. Bands of trellis work in verandahs and sunshades will have a similar effect, and roller blinds can be adjusted as required.

Surface drainage should be arranged for by sloping off the ground all round a building for, say, 10 feet at a slope of about 1 in 10, and leading off the drainage by tiled or concrete gutters with clear outfalls. Subsoil dampness should be disposed of by drains excavated outside the foundations, and filled with open porous material protected by an earth cover; they also, should have clear outfalls. Kitchen and stable sullage water should be led well away from the out-houses by impervious drains.

The annual cost of a building depends upon—(i) the interest on its capital cost; (ii) the depreciation allowed on that cost; and (iii) the charge for maintenance and repairs. The interest is a fixed percentage on the capital expenditure, the amount of which should therefore be reduced as much as possible by careful planning, and simple but sound construction. The depreciation is also a fixed percentage on the capital cost, but its rate should vary with the nature of the construction, being least when that is of the most durable character. Inferior work will thus prove dear eventually, besides being insanitary and producing discomfort to the occupants. Maintenance and repairs are generally limited to a percentage on the capital cost. The rent should cover all the three items of charge, of which the first two depend upon how the building was constructed; it is only the third one with which those responsible for its upkeep can deal. The more it is reduced, the more may the others be increased, and thus the accommodation can be enlarged, which is what occupants usually desire. In England internal repairs are effected at the cost of the tenants and this automatically induces economy: the same system could not be applied in India with its frequent compulsory changes of occupancy by transfers. The best arrangement there will apparently be to limit by rule the annual expenditure permissible on internal decorative repairs, and for the engineer himself to see that money is not frittered away on needless external repairs.