PRINCIPLES
OF
IRRIGATION ENGINEERING

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ARID LANDS, WATER SUPPLY, STORAGE WORKS, DAMS, CANALS, WATER RIGHTS AND PRODUCTS

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PREFACE

In the following pages an attempt is made to give an outline of the fundamental questions involved in undertaking and carrying out an irrigation enterprise. In presenting this matter in the form of a treatise on Irrigation Engineering, it is intended primarily for the use of students and engineers who desire to become acquainted with the general principles involved in considering the feasibility of, and in planning, constructing and operating irrigation systems. An attempt has also been made, however, to present the subject matter in such form that it may be read with profit by persons interested in irrigation, but without a thorough technical knowledge of the subject of hydraulics.

It is not possible in a book of ordinary length, to go into all of the details essential to successful irrigation construction and operation. The broader and more general aspects of the subject therefore are presented with the assumption, that where further details are necessary, it will be possible for the student to find them in one of the many technical books now available. The purpose of the work is therefore to assist the student and engineer by pointing out the essential questions to which special attention must be given.

In attempting to give this broad survey, the presentation has been made as simple and concise as possible. It is appreciated that even with engineers of large experience, there are certain broad principles, which though elementary, are worthy of frequent reconsideration. These principles when applied to new problems are frequently suggestive of different viewpoints and lead to a more thorough understanding of the work in hand. The designation, "The Principles of Irrigation Engineering," has thus been selected as indicative of the attempted scope of the work.

Irrigation Engineering in its broadest aspects may be defined as the development of the water resources of the arid regions as relating to their conservation and use as a part of the wealth of the nation. More specifically, it deals with the methods of holding, controlling and distributing the waters needed in agriculture, and further, those matters which lead to financial success in the investments then made. As a science or branch of knowledge, it is the result of investigations worked out and information collected and systematized. It should furnish knowledge concerning the water supply and its use, especially as applied to human needs and happiness. It may be studied from the point of view of the statesman concerned with questions of public welfare, by the capitalist seeking an investment, and by the engineer, called upon to plan irrigation works.

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PRINCIPLES OF IRRIGATION ENGINEERING.

CHAPTER I

IRRIGATION

Definition.—Under the term "irrigation," as applied to agriculture, is included all of the operations or practices in artificially applying water to the soil for the production of crops.

Irrigation at the present time, considered from the standpoint of the irrigation engineer, includes the conservation and storage of the water supply, the carrying of water from the source of supply to the irrigable area and distributing it to the lands. It involves, in many cases, the development and bringing to the surface, waters from underground sources, and also the raising of water by pumping or other means to lands which cannot be reached by a gravity flow from the source of supply. Closely related to irrigation is also the question of drainage for the removal of excess waters from the land.

Drainage, either by natural or artificial means, is equally as important as irrigation to insure successful agricultural operations. It is generally impracticable to apply water to lands sufficient to grow crops without a portion of it being wasted either on the surface or underground. This waste, or excess, must be removed either through natural outlets or artificially constructed drainage ditches, in order to prevent the land becoming waterlogged or charged with alkali and rendered unfit for successful farming.

In addition to the physical problems involved in irrigation, economic questions must also be considered. These questions involve estimates on the value of lands to be irrigated and a comparison of these values with the cost of constructing irrigation works in order to determine whether the project is feasible from a financial standpoint.

History and Development.—The practice of irrigation is older than civilization. It originated doubtless in the semi-tropical and relatively arid regions, where there is a periodic overflow of the desert areas traversed by some of the large rivers like the Nile. These streams, coming from plateau or mountain regions, are swollen by seasonal rains or melting of snow. Mankind in the early stages of development learned to guide or assist this overflow by rough dikes and rudely constructed ditches, later building canals to bring the water out to lands which would not be overflowed naturally, and thus gradually becoming independent of the natural rise of the stream. Before historic times the practice of irrigation had been recognized to such an extent that rules relating to the handling of water were embodied in the earliest of known writings. In the code of Hammurabi (2250 B. C.) it appears that provisions were made to cover similar troubles and controversies that are being met to-day. Laws concerning the distribution of water and guarding against waste or damage to a neighbor's field through carelessness may be copied and applied to modern conditions from the oldest of recorded regulations. In nearly all of the countries bordering the Mediterranean and to the east in Mesopotamia, India and China, the art of irrigation was practised. The early writings on the discovery and conquest of Mexico and of South American countries casually mention the irrigation canals as part of the features of the country.

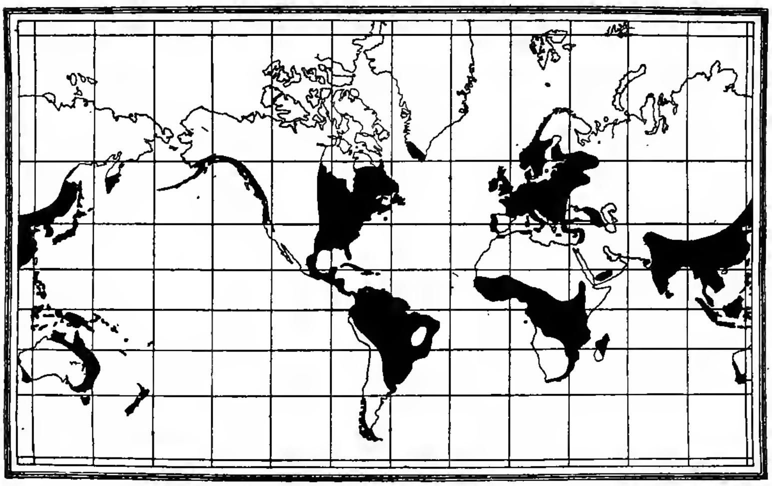


FIG. 1.—Humid regions of the world, indicated in black; arid or non-productive regions indicated by uncolored land areas.

The relative location and position of the arid regions of the world are indicated by the black areas on the accompanying diagrammatic map (Fig. 1). This illustrates how small are these humid areas, as compared with the total land surface enclosed within the outlines and left blank as indicating conditions where plant life is dependent largely upon an artificial supply of water or where the climate is too cold for the production of most of the ordinary crops. As indicated on this diagram, the greater part of western Asia and the Mediterranean countries within which civilization has developed are arid or semi-arid; also the greater part of the western half of North America including a considerable portion of Canada, Mexico, and the United States.

In the southwestern portion of the United States, especially in Arizona and New Mexico, remains of irrigation works have been found which were constructed and operated prior to any recorded history of that section. In the valley of the Rio Grande, irrigation was practised by the native inhabitants before the advent of Spanish explorers in the early part of the sixteenth century. The early Spanish missionaries also constructed irrigation works in that valley some time during that century. This, so far as known, was the beginning of modern irrigation in the United States. Some of the works constructed by the early Spanish settlers have been in use almost continuously up to the present time.

In 1847, irrigation was begun by the Mormon settlers in the Salt Lake Valley, Utah. This was the beginning of Anglo-Saxon irrigation in this country. The next irrigation development of any magnitude was about twenty years after work was started in Utah, when it was taken up in Colorado and California. From these parent colonies it gradually spread to the other states of the arid west.

The first attempts at irrigation, as previously stated, were primitive in character and consisted principally in assisting nature in carrying water over the low bottom lands during the flood period. The next step was the diversion of water from the streams and conducting it by means of crudely constructed canals to the lands. The first ditches constructed throughout the west consisted of simple furrows for turning part of the flow of a creek to the low-lying bottom lands. Diversion works, in many cases, consisted of temporary dams of bags of sand placed in the stream to raise the water slightly and divert it to the canals. When not in use, canals were frequently closed by means of an earthen embankment. When water was desired in the canal, the embankment was wholly or in part removed. In the construction of these early canals engineering advice was rarely sought, grades were fixed by the eye or by the flow of water and locations made to conform to the contours of the slopes.

In general it may be said that the advances in irrigation, the oldest of agricultural practices, have been made but slowly. It was not until comparatively recent times that the larger problems pertaining to storage and conservation of water supply were undertaken. Within the past few years remarkable progress has been made in this direction. The ultimate limit of the amount of land which can be brought under irrigation in the arid west depends largely upon the further conservation and storage of water supply and improved methods of transporting, and applying it to the soil.

Needs and Benefits.—The need of irrigation arises from lack of natural rainfall at the times when required by crops. In some regions the total precipitation annually is apparently adequate for all vegetation, but frequently the rain occurs at seasons when it is not needed and fails at critical times, thus irrigation must be practised during the season of summer drought. Under these conditions it may be considered as a form of insurance, while in the truly arid areas it is an absolute necessity.

The benefits which are derived from irrigation are those which arise from the ability to supply the amount of water needed by the growing plants in the quantity and at the times when it is most beneficial in crop production. In the arid or dry regions where rainfall is irregular or spasmodic there are consequently few clouds, the sunshine reaches the soil without obstruction and where water can be supplied this continuous unobstructed daily sunshine stimulates plant growth to a high degree, because of the well-known fact that all life and growth on the earth is maintained by the sun's energy.

Irrigation affords ideal conditions for agriculture, since with the life-giving sunlight and a means to supply moisture at proper times and in the exact quantity needed, agriculture can be reduced more nearly to scientific accuracy.

It is largely because of these facts that agriculture in an arid region offers larger opportunities for returns from a given area than in the humid regions, where dependence must be placed upon an erratic rainfall. The amount of sunlight in the humid areas and consequently the forces leading to growth are limited by the many cloudy days. Ignoring this fact, it has sometimes been urged that the same amount of energy and investment put in the agricultural operations of the eastern part of the United States should be equally or more productive than in the western, but, in this statement, there is a neglect of consideration of this all-important item of total amount of sunlight.

Methods of Irrigation.—Ordinarily, water for irrigation purposes

FIG. A.—Diverting dam in Boise River, Idaho, a typical structure for taking out river water by gravity.

FIG. B.—Main northside canal of Minidoka Project, Idaho. Illustrative of the larger irrigation canals, with power transmission lines located on the bank.

PLATE I

FIG. C.—Water being distributed to the fields through furrows after having been diverted from the river by gravity canals.

FIG. D.—Water being applied to the fields by flooding.

is conducted from some stream or lake by means of open canals dug in the rocks or earth, similar in many respects to the drainage ditches commonly used in humid regions. In fact, the resemblance between the irrigation canal and a drainage ditch is so great that the word "ditch" is commonly applied to the small irrigating canal, although it is preferable to limit the word "ditch" to its original application in drainage.

The main canal, designated to bring water to a given area, heads usually in some perennial stream and takes water from it either by means of a dam or obstruction in the river, forcing some of the water into the canal (see Plate I, Fig. A) or the water is diverted by building the inlet gates at a level sufficiently low to permit it to flow from the stream into the head of the canal. From this point the canal is built on a gently descending grade less than that of the stream from which a supply is derived, that is to say, if the stream falls at a rate of 10 ft. per mile, the irrigating canal may be built with a fall say 1 ft. per mile and at the end of 10 miles the canal will be 90 ft. above the bed of the stream. To build such a canal in ground which will sustain it, the canal after bordering the stream for a short distance must turn from it, skirting the valley and thus partly surrounding a considerable body of land which becomes wider and wider between the canal and the river. Water released from the canal will flow down the natural drainage lines back to the river, or it can be kept up on the higher ridges and thus brought to the highest points of most of the farms between it and the river.

The canal divides or sends off branches and these again send from their sides other smaller branches, sometimes called laterals, dividing and the sub-dividing until each farm is reached. (See Plate I, Figs. C and D.)

Earthen canals necessarily lose a considerable amount of water by percolation or seepage into the soil, especially if this is sandy or gravelly. There are also small losses by evaporation from the surface. Where water is very valuable the loss by percolation is frequently reduced by lining the canals with masonry or other impervious materials, or by confining the water in pipes as is the case of city supply.

Water having been brought to the area to be irrigated, there are a variety of ways in which it is applied to the land. One of the common methods, ordinarily known as "flooding," is to deliver the water to the highest portion of the land and allow it to flow downward over the slope until the entire area or field to be irrigated has been covered. (Plate I, Fig. D.) Another method, sometimes called the "check system," requires that the land be divided into small areas, each surrounded by a check or border of earth a few inches in height. Water is turned into each of the small areas until it is covered to the required depth. This method has advantages over ordinary flooding in that the amount of water applied to each portion of the land can be more accurately controlled. In the "furrow system," water is carried over the land in small furrows (Plate I, Fig. C), excavated by means of a plow or other suitable appliance, a few feet apart over the entire area. Still another method, known as "sub-irrigation," consists in bringing the water below the surface by means of pipes laid in the soil and allowing it to escape through small openings in the walls of the pipes. This method, while theoretically nearly perfect, is ordinarily prevented by the excessive cost.

Comparison of Irrigated and Non-irrigated Lands.—The advantages of irrigation are best expressed in values of crops per acre on irrigated and non-irrigated areas. Unfortunately it is difficult to make a comparison of this kind on account of the lack of comparable data relative to crop values in different sections of the country. There are examples where special crops grown without irrigation have yielded greater returns per acre then other crops grown with irrigation. There are few if any examples, however, where non-irrigated orchards have been known to produce crop returns equal to those under irrigation. The same may also be said of the more staple farm crops and especially is it true for vegetables and what is known as truck farming.

In general, it is believed that in a well-irrigated region the values of ordinary farm crops are from 50 to 75 per cent. greater than in an equally well-farmed section of the humid region. Evidence of this fact is shown by the relative land values upon which the crops are made to pay returns, and the size of farms required to support a family.

The difference in value is particularly marked in the case of the more valuable fruits because of the fact that with complete regulation of the water supply the size and quality of the fruit may be more closely controlled. This same condition applies also, but possibly in a somewhat less degree, to the growing of forage, vegetables and other staple crops. Irrigation consequently offers possibilities of intensive argiculture and of dense population, such as is not practicable where dependenee for a water supply must be placed upon rainfall.

In making a comparison of the values of products from an irrigated and non-irrigated region, it must be assumed that equal skill and energy is involved and that the cost of labor, means of transportation and character of markets are approximately the same. Even with this assumption, which is in many cases less favorable to the irrigated areas, they generally show larger average crop returns.

It is frequently the case that farmers practising irrigation are doing so without the long experience which has been had in the humid regions. Most of them have come from regions where dependence is placed in rainfall and many of them must unlearn the practices laboriously acquired and handed down for generations in order to make a success of irrigation farming. Others are men with but limited experience in agriculture who must pay for the experience they acquire by occasional failure.

Irrigation in many parts of the United States is still in a pioneer condition so that the averages of productions are not fairly comparable with those from the older humid regions. This is in part on account of the soil not being fully subdued and brought to the point where large crop returns can be expected, and partly on account of the lack of means by the settlers to carry on operations in the most efficient manner.

CHAPTER II

IRRIGABLE LANDS

Arid Region.—In the arid regions are the best and largest examples of irrigation, as here it is a necessity, while elsewhere it is more of the nature of an insurance for crops. The arid regions of the United States are part of those of the North American Continent which extend from about Central Mexico northerly in a widening belt across the United States and into Canada. They are generally defined as the localities having less than 15 inches of annual rainfall. They consist for the most part of elevated plateaus or broad valleys broken by mountain ranges, the higher slopes of which have a humid climate. Thus the arid regions are not continuous, but are interspersed with areas of humidity, from which come the streams so essential in irrigation development.

Aridity is a consequence of the continental structure and is a resultant of the atmospheric circulation of the globe, which cannot be controlled or modified in any appreciable degree by the work of mankind. It has been the dream of all the ages that mankind might influence the distribution and quantity of rainfall, primarily by occult or supernatural agencies, by incantations and various ceremonies. The later manifestations of this hope have been in the efforts to bombard the heavens, and by concussions resulting from great explosions to bring about the production of rain. It has also been hoped from a more rational standpoint to modify the quantity of precipitation by preserving or increasing the forest cover on the uplands. All of these have failed, and there is now a more general recognition of the fact, as before stated, that the formation of rain is due to world-wide rather than to local conditions.

Roughly speaking, it may be stated that the arid regions of the United States lie from about 102nd meridian west of Greenwich, or about the western limit of Kansas, westerly to the Pacific Coast, in southern California, and to the Cascade Ranges of northern California, Oregon and Washington. To the west of these, the humidity is great and it thus happens that in the state of Washington there is extreme aridity on the east of the mountains and equally extreme humidity to the west of them.

As before stated, there are scattered through this vast arid region considerable areas of relatively humid mountain masses, especially in northern portion of western Montana and in northern Idaho. The relative position and extent of the arid, semi-arid and humid regions of the United States are shown in Fig. 2.

To the east of the truly arid region is a broad belt of country, several hundred miles in width, with progressive decrease from the extreme aridity of the high plains to the moderately humid conditions of the lands of the Mississippi Valley. This broad belt is by no means fixed, as in some seasons when the rainfall is deficient, the arid or semi-arid conditions progress to the eastward and again retreat with the non-periodic fluctuations or successions of wetter seasons. Thus there is a broad belt of country of which western Kansas is typical, having a soil of exceptional fertility, one which has not been washed by the rains, but which has alternately a climate too dry for successful production of ordinary crops, followed by years of conditions highly favorable for profitable agriculture. These are the conditions which lead to what is sometimes known as the famine regions of the world, where the richness of the soil tempts agriculture, and where successive years of moderate precipitation encourages the development of population to be followed by dry years with resulting poverty and suffering.

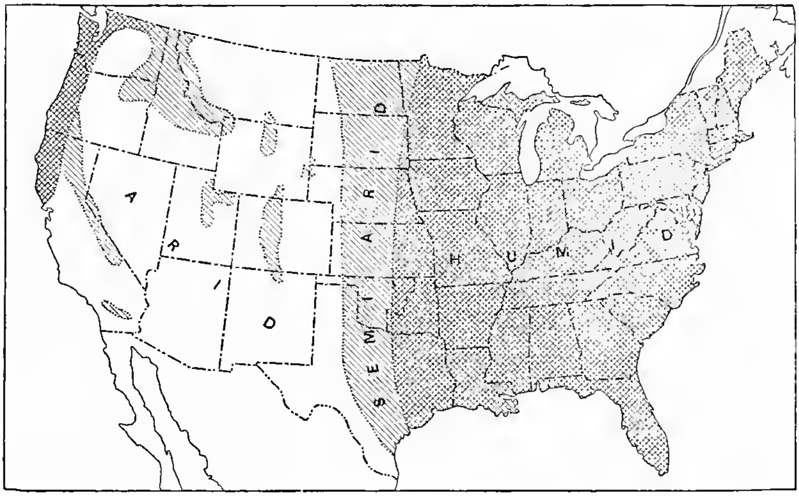


FIG. 2.—Map showing relative area and position of arid, semi-arid and humid regions of the United States.

Topographic Features.—The arid region of the United States as a whole is relatively high, including as it does the great plateau of the Rocky Mountains or Cordilleran area. The general slope from about the center of the region toward the south is such as to bring the arid lands down to or even below sea level, as in the case of Death Valley and the Salton Desert in southern California. Toward the north there is also a general decline in altitude, but far less marked than toward the south. The climate of the northern portion of this arid region is modified and less rigorous on account of this descent toward sea level.

The mountain masses which traverse the arid regions serve to force upward the prevailing winds, causing them to deposit their moisture on the slopes. These have a relatively heavy precipitation as testified by the presence of the forests which extend from the timber line well down the sides toward the dry valleys. These forests for the most part have been segregated from the public domain of the United States and set aside as reservations or National Forests (see Fig. 3) under the charge of the Forest Service of the Department of Agriculture. The primary object of creating these reserves has been for the protection of the timber supply of the country, but a secondary and sometimes more important object to be attained is the beneficial effect which forest cover has on the water supply so necessary for agricultural development in the valleys.

These scattered mountain ranges and isolated peaks, thus give rise to innumerable streams, some of considerable size. These coming with steep slopes toward the valleys render the conditions favorable for economical development of irrigation. In Utah, for example, the almost innumerable small streams from the Wasatch Mountains issuing upon the desert valleys at frequent intervals, enabled the pioneers to build their small irrigation canals at the minimum of cost. Relatively few large structures were required and the steep slopes permitted the water to be carried out in narrow channels but still at a sufficient elevation to cover the irrigable lands in the valleys below.

The Soil.—The soil of the arid regions differs essentially from that of the humid regions in that disintegration has taken place under conditions where the earthy salts have not been so completely leached out. Many of the soils have been built up by wind action, others are alluvial or delta deposits brought out upon the margin of the valleys by the streams issuing from the high mountains. Still others have resulted from sedimentation in fresh-water lakes.

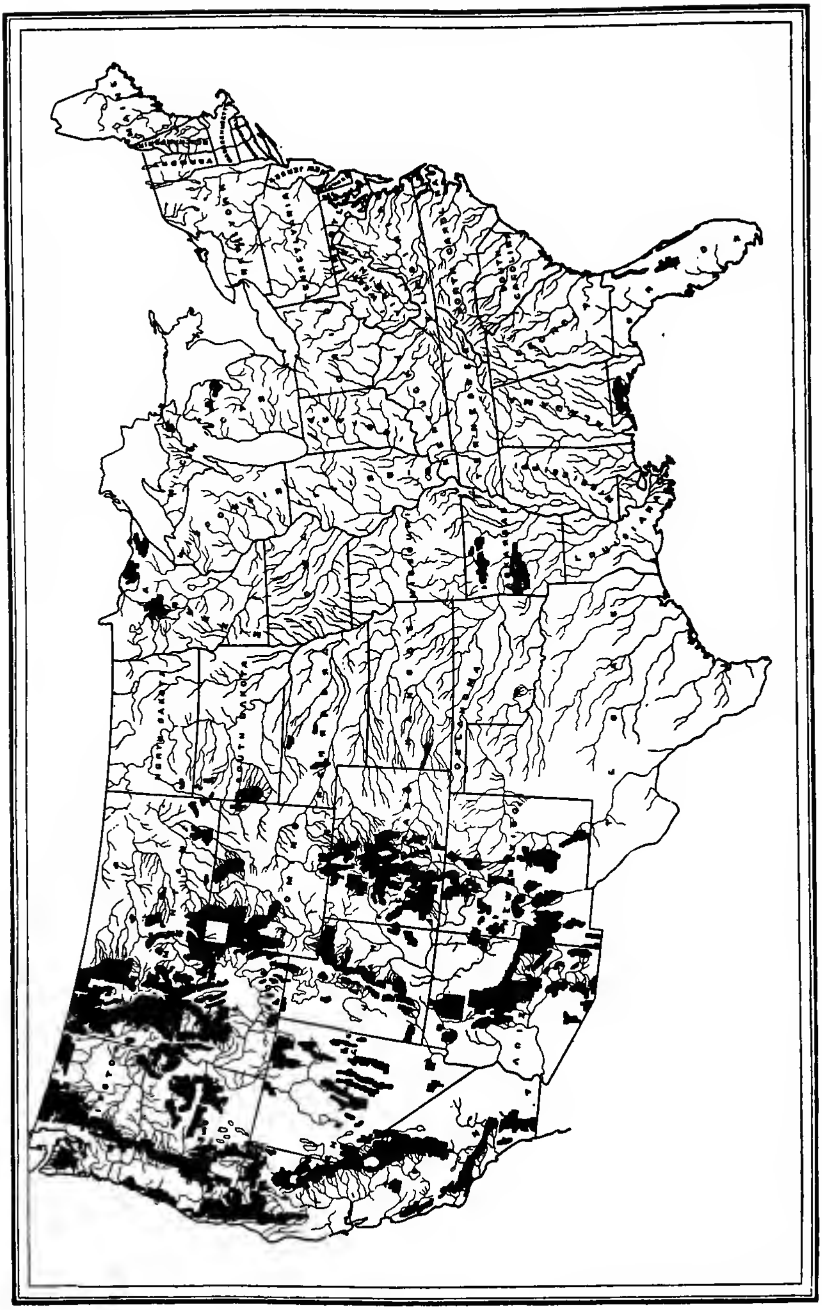


FIG. 3.—Map showing relative position and extent of the National Forests. (Indicated by black areas.)

As a whole, the soils are more highly productive in their natural condition than those of the humid regions, excepting possibly those of the swamp lands.

One of the most notable characteristics of the agricultural soils of the arid region is the deficiency of organic vegetable matter. The first effort of the skilled irrigation farmer is to supply this lack. Fortunately, alfalfa, one of the most valuable of the forage plants, is also valuable for supplying organic matter to the soil. This plant also has the property of obtaining nitrogen from the air, and giving it to the soil, through the activities of bacteria which inhabit nodules on the roots. As soon, therefore, as the soil has been broken up and partly subdued by planting a grain or similar crop, alfalfa is put in and after a few cuttings the green plants are plowed under, thus supplying the soil with the necessary organic matter, and making it capable of producing subsequently large crops of potatoes, sugar beets, or other vegetables.

Preparation of Lands.—The first and most important step in preparing the lands for irrigation is to smooth and level the surface as accurately as possible. If this is once properly done, it will be possible to till the soil year after year, and apply water with a minimum amount of labor and loss. If it is not carefully performed there will always be difficulty in thorough irrigation with resulting uneven growth of plants due to the fact that water has been applied more plentifully in some spots than in others.

In its native state, most of the best agricultural land is covered with sagebrush. Other lands have the so-called greasewood or similar desert vegetation, nearly all of which is easily removed by dragging with a heavy iron bar or by using heavy machines made especially for the purpose. Having removed the sagebrush, the next step is to break up the ground with a plow, and then, as above stated, to smooth and level it into small fields or "lands," using for this purpose a scraper or drag by which the higher knolls are shaved off and the depressions filled.

Where heavy winds prevail, especially in the spring, particular care must be taken not to remove at once all of the sagebrush or other desert vegetation, because by so doing the winds have access to the loose soil and readily blow it away, cutting out the seed or young plants. By leaving rows of sagebrush across the path of the wind and cultivating the intervening strips, the surface is protected until the plants thoroughly shade the ground; it is then possible to take out the windbreaks and cultivate the remaining soil. By the exercise of skill and forethought it is thus possible to get into crop lands which otherwise could not be handled. After the first few years of cultivation, especially after a certain amount of vegetable matter is gotten into the ground, the tendency of the soil to be moved by the wind is greatly decreased and by planting trees for windbreaks and taking other precautions, the difficulties encountered by the pioneers are successfully overcome.

Location.—There is more land than water with which to irrigate in most parts of the arid region. For a given water supply there is usually possible a choice of lands not merely with reference to physical characteristics but with regard to accessibility to markets or lines of communication. The arid region, as a whole, is sparsely populated, there being few notable cities, but with the development of the railroad systems, it is now possible to reach nearly all the irrigable lands with relatively short wagon roads. Much of the success of any irrigation project depends upon the choice of lands in such way that the distance to markets and cost of transportation will be as small as possible.

The west is favored in the fact that the precious minerals are quite widely disseminated and at the mining camps there is usually an excellent market for everything which can be raised under irrigation. In fact the two occupations are interdependent in that the development of agriculture in the vicinity reduces the cost of living and consequently the cost of mining, so that the lower-grade ores can be handled and the development of these mines gives a needed market for the crops.

Intensive Farming.—The large amount and intensity of degree of the sunlight and favorable condition of soil as compared with the humid regions render it possible for the average farmer to be supported on a much smaller tract of land than is the case in the non-irrigated portions of the United States. The expense of building long lines of canals results also in bringing the farms close together and in utilizing to the fullest extent possible all the lands within a given district. The irrigated areas are not only capable of the most intensive cultivation but all of the conditions of water supply and of transportation favor the most complete development.

The high price of labor which prevails through the western part of the United States results in the greater part of the work on each farm being performed by the family living upon it, and this in turn tends to keep down the area of each farm and increase the economics and the product per acre. As time goes on, with greater increased capacity for production and with growth of population, the farms are further sub-divided; there is a marked tendency toward still more intensive cultivation and with corresponding increase in values the occupation of smaller and smaller areas per family, the standard of living increasing with the higher productivity of soil.

Climate.—The climatic conditions are those generally known as continental and are correspondingly extreme with cold winters and hot summers. The dryness of the air renders these extremes of temperature less burdensome than they would be in more humid portions of the country. The summers, with their continuous daily sunshine, even though relatively short in the north, are conducive to large crop production. In the southern portion of the arid regions, for example in Arizona, crop growth continues practically throughout the year, there being hardly a perceptible rest of plant activity during the winter, so that crop follows crop in succession as rapidly as it can be matured and removed. As far as human health is concerned and that of domestic animals, the extreme aridity seems to be highly beneficial and is in general recommended.

CHAPTER III

WATER SUPPLY

Source of Water Supply.—The principal source of water supply for irrigation is from the perennial streams which issue from the higher mountains. A relatively small but increasingly important amount of water is derived from floods which are held in reservoirs and a still smaller proportion from natural storage in the ground, the water being recovered by wells sunk in the gravels or sands of the valleys.

The streams which have their source in the high mountains are maintained not only by the rainfall on the mountain sides but are increased in volume by the melting snows. With their large supply from the forested areas they are the most nearly ideal for purposes of irrigation. The annual floods occur at a nearly definite date and it is possible to plant crops with reasonable assurance of an adequate amount of water for ordinary irrigation. These are the sources of supply which have been first utilized and which are now in many instances over-appropriated, that is to say, the claims for use of water aggregate more than the usual flow.

In distinction from mountain streams are those which have a less elevated catchment area, and which depend for water upon the less regular rainfall. These are occasionally in flood but for the greater part of the year are nearly or quite dry and cannot be depended upon. Irrigation has been tried along these streams and considerable investment made but with little success, as the headworks are frequently washed out by the erratic floods, and before they can be restored the stream has usually gone dry. In nearly every case it is necessary to provide, wherever possible, large and expensive reservoirs out on the plains in order to regulate the supply. Even then there is considerable uncertainty owing to the fact that the rainfall in these lower regions is not as uniformly distributed as it is on the higher summits.

Character of Supply.—From what has been stated, it is apparent that there is a very great difference in the amount and reliability of supply to be had from different streams. Those coming from the mountains with forested and lofty catchment areas afford the fewest problems, as their flow is relatively steady, while those coming from lower and more open regions offer increasingly difficult questions, and necessitate the careful study of all opportunities for providing storage reservoirs.

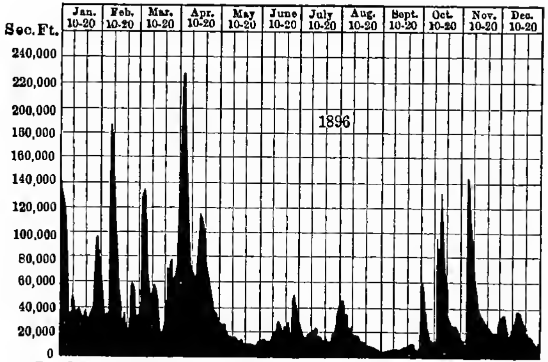
The accompanying diagrams, Fig. 4 and Fig. 5, illustrate the difference in behavior of typical rivers of the eastern humid part of the United States, and of the western arid portion. In Fig. 4 is indicated by the position and height of the black areas the relative quantity of water expressed in cubic feet per second or second-feet, occurring throughout the year. The diagram illustrates the fact that the greater portion of the water in the Susquehanna River at Harrisburg, Pa., occurs in the spring, with summer drought, most notable in the latter part of August, and early in September. In the case of the Yadkin River at Salisbury, N. C., the greater portion of the water occurred in short quick floods in the latter part of the summer and early in the autumn, these being the result presumably of heavy storms on the mountains.

In comparison with this is the diagram for the Gila River at Buttes, Ariz., showing a very small relatively steady flow during the early part of the year followed by erratic floods due to so-called "cloud bursts" on the drainage basin. In marked contrast to this is the large comparatively uniform flood in the Green River at Blake, Utah, typical of the streams which come from the snow-clad mountains, the water being supplied by the melting of the snow as summer advances.

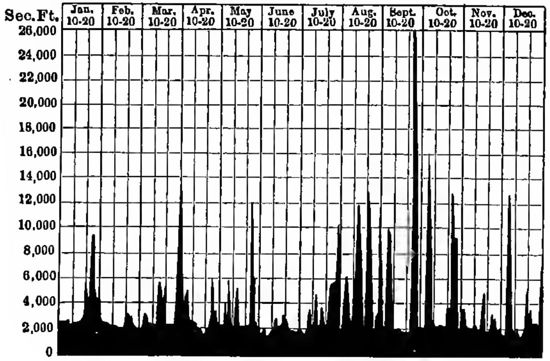
A record of the behavior of the streams of the arid region, as well as those of the humid region, has been undertaken by the United States Geological Survey and beginning in about 1888, systematic observations have been conducted on many rivers and creeks. It has not been possible to measure all of the flowing waters, but the attempt has been made to select typical streams which would be fairly representative of others in the vicinity.

The height of water at selected points has been observed and recorded day by day, and the quantity of flow corresponding to the various heights has been ascertained. By means of these data it has been possible to compute the total flow at the observed points by months and seasons, giving figures of the amount and duration of floods and of the low-water periods.

Benefits of Control.—The benefits which arise from the ability to store these flood or waste waters need hardly be enumerated. These waters unregulated frequently occur in quantity sufficient to

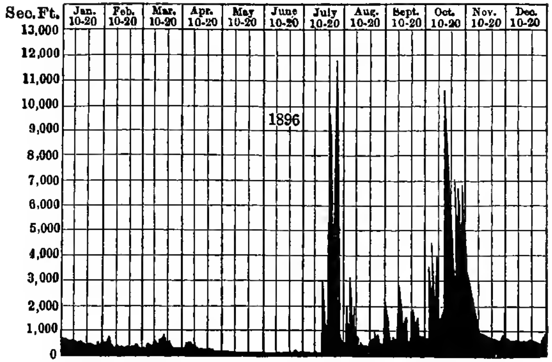


Discharge of Susquehanna River at Harrisburg, Pennsylvania, 1896

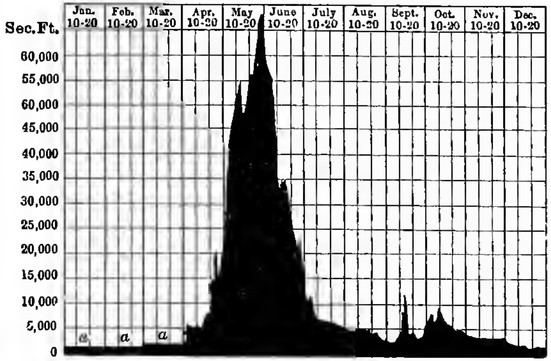


Discharge of Yadkin River at Salisbury, North Carolina, 1898

FIG. 4.—Diagram of discharge of two typical rivers of the humid region.



Discharge of Gila River at Buttes, Arizona,



a Approximate

Discharge of Green River at Blake, Utah, 1897

FIG. 5.—Diagram of discharge of two streams in the arid region.

destroy bridges, dams and other structures along their course or to overflow the farms and villages on the lowlands. By holding back th floods, which if unregulated would be a source of destruction, it is possible to use this water in the reclamation of waste and useless land and thus provide opportunities for citizens and their familier who otherwise would not be able to obtain a foothold on the land. From the standpoint of the stability of the commonwealth, there is perhaps no engineering or economic operation which has a deeper significance or is of greater value than this practical application of the principles of conservation.

By a study of the data obtained from systematic measurements it has been possible to arrive at certain conclusions with reference to the practicability of conserving the waste waters and holding them wherever suitable natural basins can be found, the outlet of which may be closed by dams at reasonable cost. The Federal Government, as the original proprietor and still the owner of vast tracts of desert land, is interested in obtaining all of these facts upon which engineering operations may be based and by which money may be safely invested in the construction of storage works for holding the flood waters and for delivering them at the proper time to the lands which may be irrigated.

Study of Water Supply.—In the study of the water supply and the practicability of storing or diverting it, the principal features of importance are the daily or periodic observations of quantities. From these a great variety of facts relative to the amount of water available from a given stream may be secured and comparisons made. At the same time it is important to obtain definite knowledge concerning the topography of the catchment area from which the water flows, and to know its cultural conditions, and whether these are likely to be changed in such way as to modify the amount of water available. One of the important factors in a water supply is its constancy or regularity of flow. In order to determine this it is necessary to have records extending over a period of years.

In choosing a water supply, preference should be given to one which is constant in character rather than one which varies greatly from year to year, even though the total flow from the constant source is somewhat the smaller.

Rainfall.—The primary factor in questions of water supply is the amount of precipitation in the form of rain or snow which reaches the earth. This varies greatly in different parts of the country, being governed quite largely by geographic or topographic relations.

Without entering into detailed discussion of these, it is sufficient to call attention to the result as illustrated by the accompanying map (Fig. 6), showing that there is a wide divergence in the total quantity of precipitation in different parts of the United States, the greatest rainfall being on the eastern coast and near the Gulf of Mexico and, on a comparatively narrow strip of country adjacent to the Pacific Ocean in the extreme Northwest. The least amount of rain which occurs is that within the interior of the country which includes a considerable portion of what now forms the states of Nevada, Utah, New Mexico, Arizona, and adjacent portions of California.

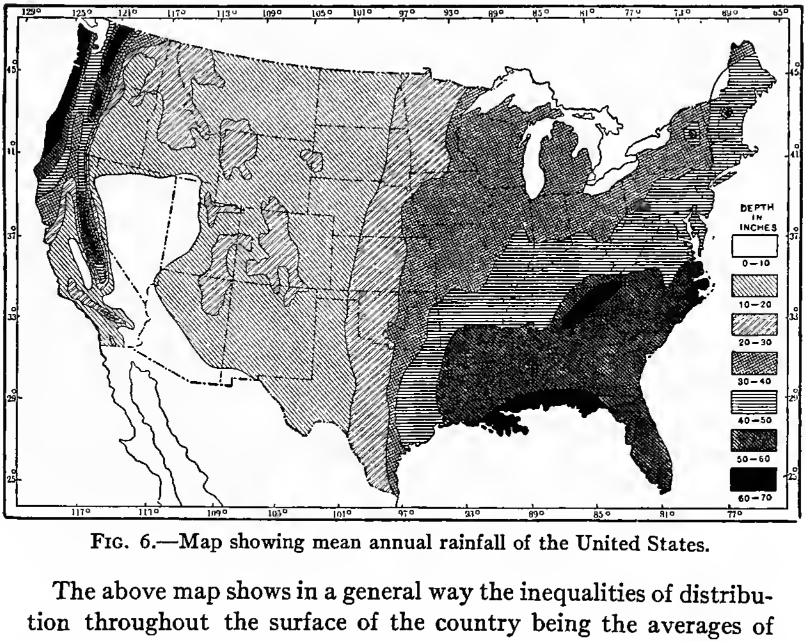


Fig. 6.—Map showing mean annual rainfall of the United States.

The above map shows in a general way the inequalities of distribution throughout the surface of the country being the averages of observations carried on through many years. For any single locality there is great divergence; during one year there may occur nearly twice as much rainfall as during some preceding or succeeding year. This is illustrated by the diagram Fig. 7 of the annual precipitation at Salt Lake City, Utah, where the average is about 16 inches, with few years which approximate this amount.

Attempts have been made to arrive at some rule or generalization regarding this irregularity of rainfall; efforts have been made to connect it with the occurrence of the sun spots and other natural phenomena. Various students have figured out, to their own satisfaction, that years of drought or flood occur with a certain general regularity in cycles of 7 years, or 11 years, or 17 years, but hardly any two of these persons will agree as to the actual facts or conclusions to be drawn from them. For most practical purposes, attention should be concentrated on the fact that whenever a relatively dry year occurs, it may be followed by an even greater drought and provision must, therefore, be made to meet a succession of relatively dry years.

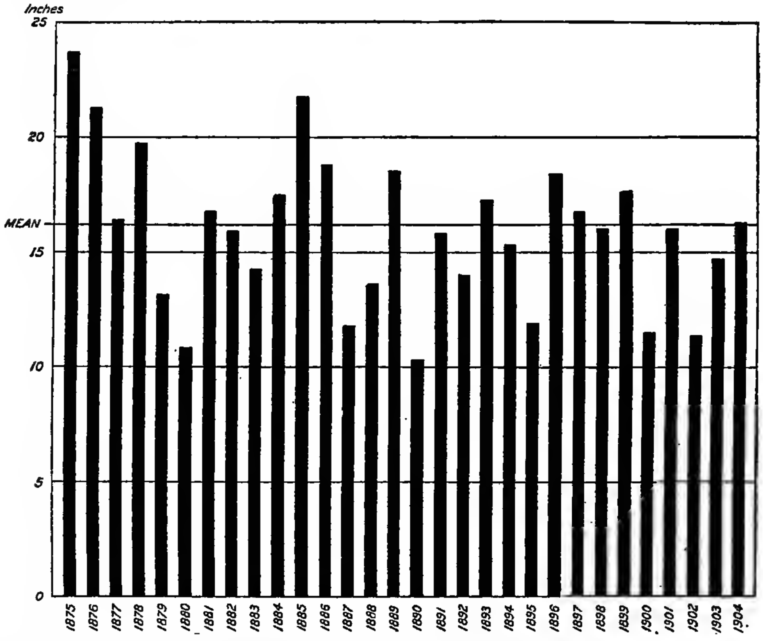


FIG. 7.—Diagram of annual precipitation at Salt Lake City, Utah, illustrating the fluctuations in total quantity of rainfall.

Runoff.—The term "runoff" was devised as a convenient expression for the water which flows off the surface of the land in the form of visible streams. The relation between the amount of water which falls upon the land in the form of rain or snow and the amount of runoff which may become available for irrigation has been a source of investigation and controversy among engineers. The inference was drawn by some engineers and physicists, from early observations on rainfall and runoff, that a somewhat definite relation existed between them and that by knowing the rainfall the amount of runoff could be calculated. The results which have followed from this theory have been highly interesting but in many cases widely at variance with actual conditions.

On certain of the watersheds in the eastern and more humid regions of the United States, where the rainfall is relatively constant in amount and time of occurrence, there seems to be a relatively consistent ratio between the rainfall and runoff. In the arid west this does not appear to exist and attempts to apply the ratios found in the humid regions of the east to the arid regions of the west produce misleading and, in many cases, ludicrous results. A case illustrating the above remarks is that of an engineer acquainted with eastern conditions only who was employed to investigate the water supply available from an Arizona river. By taking the rainfall of the area and using what he considered a conservative allowance, namely, about 20 per cent. for runoff, he reached the conclusion that a certain amount of water would be available. It so happened that measurements had already been made which showed the runoff to be a little more than 2 per cent. of the rainfall. The engineer in question was very sure that there must be an error in printing the records of stream flow, since his careful analysis had demonstrated to him that the water which theoretically would be available was ten times that found by direct observation.

Influences affecting Runoff.—A clear conception of the varying character of runoff can be obtained by considering it as the excess of water on a given area after all of nature's requirements for moisture on that area have been supplied. It is the balance, so to speak, between nature's supply and immediate needs. If no more water falls on a given area than can be taken up and absorbed by it the resulting runoff will be nil. The time allowed for water to be taken up either through the soil or the atmosphere, as will be seen later, also plays an important part in determining how much will be absorbed and how much will be carried away by streams.

The principal factors which affect directly the amount of runoff are: amount and character of rainfall, character of watershed, and evaporation. All of these are varying influences of so complex a nature that it is impossible to determine any accurate measure of their value. It is possible in some cases to find watersheds where conditions will give nearly the same amount of runoff on each of them. Where this is the case, an estimate of the runoff from an unknown area may be obtained by comparing it with that of a similar area where measurements have been made.

The first and most important consideration for runoff is rainfall.

It does not follow, however, that rainfall always produces runoff. It is a significant fact that a certain amount of rainfall is required before any runoff will result. This minimum amount will vary for different watersheds and climatic conditions. It is also true that the ratio of runoff to rainfall increases with the rainfall. The first question then is whether the total rainfall on a given area is sufficient to produce any appreciable runoff. Granting that this be the case, the next question is to determine what amount of runoff may be expected.

If the rainfall occurs in heavy, copious showers, so that only a small amount has time to soak into the soil, the greater part may be carried away over the surface and eventually be collected in the streams below. The same amount of rainfall occurring in a slow steady drizzle may be entirely absorbed by the soil and add nothing to the stream flow. If precipitation comes in the form of snow and, as is frequently the case, is banked up in the ravines, it may be held well into the summer months, acting in the meantime to supplement the stream flow at a more or less uniform rate.

Character of Watershed.—The steepness of the slopes, kind and depth of soil, and the presence of vegetation upon a watershed will influence in a marked degree the amount of runoff. Where water falls upon steep slopes it flows away rapidly and before a large part of it can be absorbed by the soil. Even when the soil becomes saturated to some depth through long-continued rains the steep slopes permit more rapid drainage and it results that a greater amount of water is carried away from them than would be the case on flat slopes otherwise similar in character. A rainfall giving as high as 30 or 40 per cent. runoff on the steep sides of a mountain range may not produce more than 3 or 4 per cent. on the lower level or gently rolling plains.

A deep porous soil will absorb and hold more water than a shallow compact one. On rock slopes practically no water is lost by absorption, hence greater runoff results from them than from earthen slopes. The presence of frost in the ground also tends to increase the amount and rate of runoff.

The flow of water is retarded if the ground is covered by a forest or other form of vegetation. More water will consequently sink into the soil under these conditions than will be the case on land devoid of vegetation. The presence of a forest cover also modifies the rate of runoff by holding back a part of the waters and permitting them to slowly trickle down to the streams. For this reason it is of value in reducing the intensity of the flood flow after severe storms.

Evaporation.—The greatest influence affecting runoff is evaporation. Its action is continuous from every part of a watershed where moisture is exposed to the atmosphere. Vegetation, wherever present, and capillary action in the soil are constantly bringing moisture to the surface of soils where it is changing to vapor. The action of evaporation, while ordinarily continuous in character, nevertheless varies greatly in amount at different times and in different localities.

The rate of evaporation depends primarily upon the capacity of the atmosphere to take up moisture and the ability of the surface to supply this moisture as rapidly as it can be absorbed. The capacity of the atmosphere to receive and dissipate moisture depends upon temperature, rate of wind movement and the degree of saturation or amount of water which it already contains. The rate at which the soil can supply moisture depends primarily upon the depth to water and the capillary action of the soil in bringing this water to the surface.

Where water stands on the surface or where the surface layer of the soil is saturated, the earth can supply moisture at a greater rate than the air can absorb it. This condition exists on the surface of lakes and ponds and upon land immediately after a rain. If the surface supply is not replenished by frequent rains the moisture disappears partly by seepage downward and partly by evaporation until a condition exists where little or no water will be supplied to the air. This is frequently the case in the extreme arid regions. The rate of evaporation for a short period after a storm may be very rapid but practically negligible for the remainder of the year. In the humid regions, where the surface of the soil is moist during the greater part of the year, the annual loss by evaporation is relatively constant.

It is evident that for a watershed from which there is no underground flow, the runoff is equal to total rainfall less evaporation. Such conditions apply closely on a large area where the underground losses, if any, from it are so small as to be negligible when compared with the total amount of water which falls on the area. On small areas of a few hundred square miles and from which the underground flow may amount to several per cent. of the rainfall, it is evident they do not apply.

Runoff on Different Watersheds.—As illustrating the difference in amount of runoff from different watersheds in various parts of the United States, the following table is presented. This table has been prepared from the records of stream gagings made by the United States Geological Survey:

MEAN ANNUAL RUNOFF FOR VARIOUS WATERSHEDS IN THE UNITED STATES

River	Point of measurement	Drainage area square miles	Period	Runoff in depth in inches on drainage area
Kern	Bakersfield, Cal	2,340	1896–1905	4.36
San Joaquin	Herndon, Cal	1,640	1896–1901	20.47
Kings	Sanger, Cal	1,740	1897–1906	20.38
Sacramento	Red Bluff, Cal	4,300	1902–1906	24.06
Umatilla	Umatilla, Ore	2,130	Nov. 1, 1900, to Dec. 31, 1900	3.94
Willamette	Albany, Ore	4,860	Jan. 1, 1899, to Dec. 31, 1908	46.62
Boise	Boise, Idaho	2,610	1895–1904	15.60
Green	Green River, Wyo	7,450	May 1, 1896, to Oct. 31, 1906	4.81
Laramie	Uva, Wyo	3,180	May, 1895, to Oct., 1903	1.10
Red	Grand Forks, N. Dak	25,100	Sept., 1902, to Sept., 1908	2.08
Rio Grande	Rio Grande, N. Mex	14,000	Jan. 1, 1896, to Dec. 31, 1905	1.46
Animas	Durango, Col	812	July, 1895, to Dec., 1905	14.86
South Platte	Denver, Col	3,840	Jan. 1, 1896, to Nov. 30, 1906	1.44
Green	Greenriver, Utah	38,200	Jan., 1895, to Dec., 1908	3.17
Logan	Logan, Utah	218	1896–1900 1904–1906	21.18
Carson	Empire, Nev	988	Nov., 1900, to Dec., 1906	6.25
Truckee	Vista, Nev	1,520	Sept., 1899, to Dec., 1906	9.18
Humbolt	Orleans, Nev	13,800	Jan., 1897, to Dec., 1906	0.25

MEAN ANNUAL RUNOFF FOR VARIOUS WATERSHEDS IN THE UNITED STATES—*Continued.*

River	Point of measurement	Drainage area square miles	Period	Runoff in depth in inches on drainage area
Colorado..........	Yuma, Ariz............	225,000	Jan., 1902, to Dec., 1906	1.15
St. Croix..........	St. Croix Falls, Wis....	6,370	1902–1904	10.60
Menominee	Iron Mountain, Mich...	2,420	Sept., 1902, to Sept., 1906	18.92
Illinois............	Peoria, Ill.............	13,200	Apr. 1, 1903, to Jan. 30, 1906	14.11
Maumee..........	Waterville, Ohio.......	6,110	Dec., 1898, to Jan., 1902	13.61
Scioto............	Columbus, Ohio........	1,050	1899 to July, 1906	10.43
Duck.............	Columbia, Tenn........	1,260	Nov. 1, 1904, to Dec. 31, 1908	18.87
Tennessee.........	Chattanooga, Tenn.....	21,400	1899–1908	23.63
Tombigbee........	Columbus, Miss........	4,440	1905–1908	15.48
Black Warrior.....	Cordova, Ala...........	1,900	1900–1908	19.37
Alabama..........	Selma, Ala.............	15,400	1900–1908	24.01
Savannah.........	Augusta, Ga...........	7,300	1899–1908	22.29
Catawba..........	Rock Hill, S. C........	2,990	1895–1903	25.21
Tar..............	Tarboro, N. C.........	2,290	1896–1900	13.89
Roanoke..........	Randolph, Va..........	3,080	1901–1905	18.86
Potomac..........	Pt. of Rocks, Va.......	9,650	1895–1906	14.40
Oswego...........	Oswego, N. Y..........	5,000	1897–1901	11.69
Delaware..........	Port Jarvis, N. Y......	3,250	1904–1908	22.20
Susquehanna......	Binghamton, N. Y.....	2,400	1901–1906	28.88
Hudson...........	Mechanicsville, N. Y...	4,500	1891–1900	22.95
Mohawk..........	Dunsbach Ferry, N. Y..	3,440	1898–1907	23.28

Comparison of Runoff.—A comparison of the runoff on different watersheds frequently leads to interesting conclusions, especially when the various factors which influence it are considered. If a comparison is made without first considering the amount and character of rainfall, the nature of the soil, and losses by evaporation, the results are not only confusing but frequently lead to far-reaching engineering blunders. For example, the earliest data available were from watersheds in New England or New York. These were fairly consistent among themselves and it was possible to deduce rules for local application to the effect that about 30 per cent. of the rainfall might be found in the stream. Engineers have some times taken these conclusions and attempted to apply them in the west, with the result that they have been greatly misled in their assumptions of available water supply.

This has been due not merely to the fact that direct comparison could not be made, but also to what should have been even more obvious; namely, that the measured rainfall in the west has been mostly in the valleys and rarely on the higher portions of the catchment area from which comes the greater part of the water.

It is important and necessary in some cases to make deductions, based upon comparisons or runoff of various watersheds, since it has not been possible to measure the runoff from every stream. When such comparisons are made, however, great care must be exercised in selecting areas which are similar in character. It is recognized that an area of 1,000 square miles may have a different character of runoff from one of 100 square miles, even in the same region, so that when it is desirable to study the amount of water probably available from a river basin of a thousand square miles, it is important to obtain the measurements which have applied to a similar area and not to one notably larger or smaller.

It must be recognized that conclusions drawn from such comparisons are at best subject to grave error, and that an accurate value of runoff can be had only by direct measurement.

Measurement of Water.—The measurement of water may properly be considered under two heads, namely, measurement of supply and measurement of duty requirement.

Measurement of supply is for the purpose of determining the quantity of water available for irrigation, power development and domestic use. It includes the measurement of runoff from the various streams and to a limited degree also the determination of underground flow which may be made available for use through pumping

PLATE II

FIG. A.—Method of making a measurement of the amount of water in a stream, using current meter from bridge.

FIG. B.—Making similar measurements by wading.

(*Facing Page 26*)

PLATE II

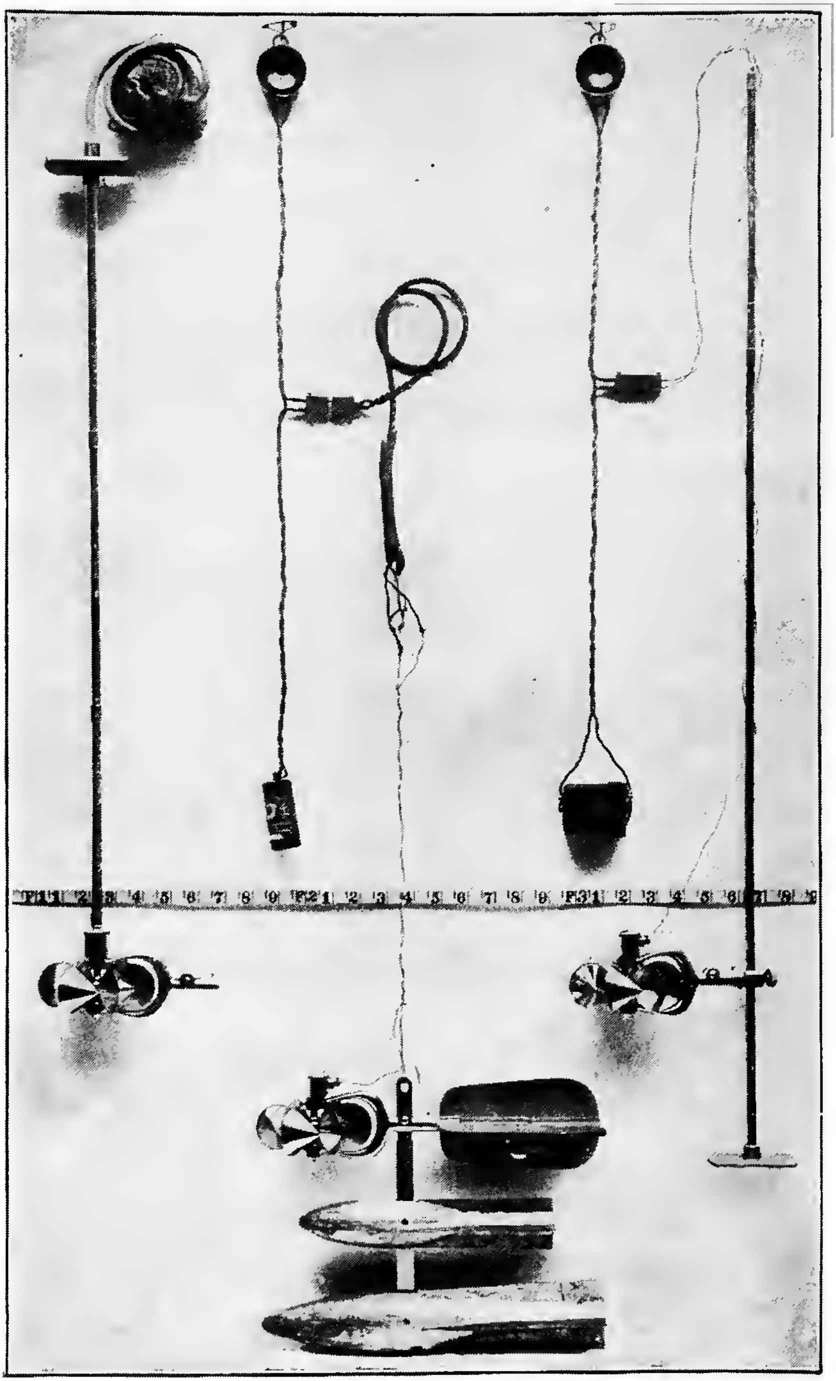


FIG. C.—Meters used for measuring the velocity of the flowing water.

or artesian flow. Measurement of duty requirement includes the determination of the amount used for irrigation, power development and other purposes.

Both of the above classes of measurements are necessary in an enterprise involving the use of water; the first to determine the amount available and the second to determine the extent of an enterprise which a given supply will furnish.

The methods of measuring water in natural streams in a systematic and economical manner have been developed within the last twenty years, largely by the efforts of the United States Geological Survey. Notable progress has been made in simplifying details and in adapting them to methodically carrying on work over a wide extent of country. There has been a gradual evolution of the instruments employed, especially along the line of lightness and portability.

Briefly stated, the work consists of measuring and recording the total quantity of water which passes a given point in a stream and in this manner determining the runoff from each of the principal watersheds. It has not been possible, up to the present time, to measure all of the streams of the country; enough, however, are being measured to permit rough estimates of the total supply being made and the work is being gradually extended with the increasing demand for water-supply data. Measurements of the quantity of water used in various enterprises are also being carried on, both by the United States and public utility corporations.

Units of Measurement.—Two classes of units are commonly used in the measurement of water, the first representing quantity and the second rate of flow.

Quantity is measured in terms of some well-defined unit of capacity and is used to express the amount of water contained in a reservoir or that applied to a given area of land in the process of irrigation. The units of quantity commonly used are the gallon, the cubic foot and the acre-foot. The gallon and cubic foot are employed in expressing the quantity of water stored or used for domestic purposes, but, on account of the smallness of each of these units, they are seldom used in engineering estimates of irrigation work. Instead the acre-foot is the common unit. It is defined as the amount of water required to cover 1 acre 1 ft. deep or 43,560 cu. ft. Capacities of large reservoirs are generally given in acre-feet, these figures being thus immediately computable with the agricultural areas.

Rate of flow may be defined as the quantity of water flowing through a pipe or channel in a given unit of time, usually the second.

The units are the miner's inch and second-foot. The miner's inch, the first unit expressing rate of flow generally employed in the United States, is supposed to represent the quantity of water which flows continuously through an orifice 1 in. square under a given head. The head on the orifice has been variously defined in different localities but is ordinarily taken as about 4 in. above the top of the orifice.

The second-foot is defined as 1 cu. ft. per second of time. A box or conduit 1 ft. square carrying water with a velocity of 1 ft. per second would deliver 1 second-foot. The second-foot, on account of its definiteness, is the most desirable unit for expressing rate of flow and the one commonly used by American and English engineers. By the latter it is written "cusec."

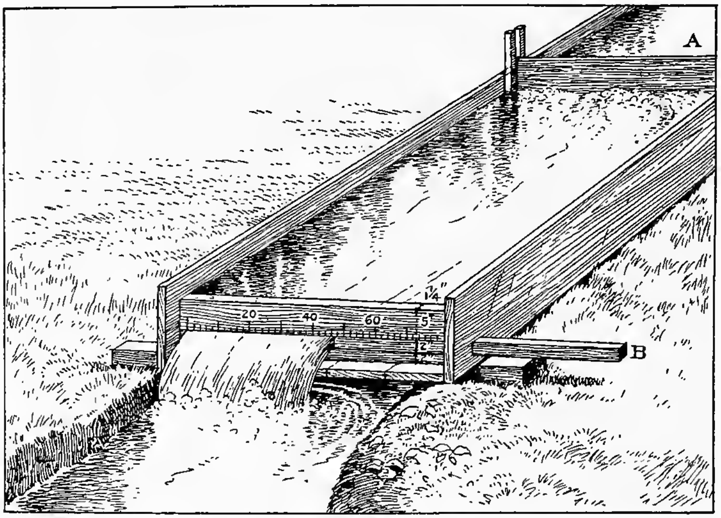


FIG. 8.—Method of measuring miner's inches.

The miner's inch is indefinite since the quantity of water which will flow through an orifice 1 in. square under a fixed head depends upon the thickness of the medium in which the orifice is made. For example, the amount of flow through an orifice cut in a plank 2 in. in thickness will be very different from that through the same size orifice cut in a thin sheet of metal.

One of the methods of measuring miner's inches is indicated by the accompanying illustration, Fig. 8, in which a rectangular orifice is so arranged as to be capable of adjustment to various widths by means of a slide, rendering it practicable to measure quantities from one miner's inch up to 75 inches. This is fairly satisfactory for these smaller quantities, but to measure 10,000 miner's inches by such device is practically impossible because of the fact that the orifice must be of great horizontal extent to avoid the complications of increased head if the orifice is enlarged in a vertical direction.

In order to avoid confusion growing out of the use of this unit, most of the states have defined the miner's inch in terms of the second-foot. In this, however, there is not an agreement among the various States. In Idaho, Kansas, Nebraska, New Mexico, North and South Dakota, 50 miner's inches equal 1 second-foot. In Arizona, California, Montana and Oregon, 40 miner's inches equal 1 second-foot.

On account of its indefiniteness and the fact that the miner's inch is not well adapted to expressing the results of computations on the rate of flow through flumes, over wiers and other measuring devices, the use of the term should be discontinued.

"Second-feet per square mile" is the average number of cubic feet of water flowing per second from each square mile of area drained, on the assumption that the runoff is distributed uniformly both as regards time and area.

"Runoff in inches" is the depth to which the drainage area would be covered if all the water flowing from it in a given period were conserved and uniformly distributed on the surface. It is used for comparing runoff with rainfall, which is usually expressed in depth in inches.

Convenient Equivalents.—The following is a list of convenient equivalents for use in hydraulic computations:

1 second-foot equals 7.48 United States gallons per second; equals 448.8 gallons per minute; equals 646,272 gallons for one day.

1 second-foot equals 6.23 British imperial gallons per second.

1 second-foot for one year covers 1 square mile 1.131 feet or 13.572 inches deep.

1 second-foot for one year equals 31,536,000 cubic feet.

1 second-foot equals about 1 acre-inch per hour.

1 second-foot for one day covers 1 square mile 0.03719 inch deep.

1 second-foot for one 30-day month covers 1 square mile 1.116 inches deep.

1 second-foot for one day equals 1.983 acre-feet.

1 second-foot for one 30-day month equals 59.50 acre-feet.

100 United States gallons per minute equals 0.223 second-foot.

100 United States gallons per minute for one day equals 0.442 acre-foot.

1,000,000 United States gallons per day equals 1.55 second-feet.

1,000,000 United States gallons equals 3.07 acre-feet.

1,000,000 cubic feet equals 22.95 acre-feet.

1 acre-foot equals 325,850 gallons.

1 inch deep on 1 square mile equals 2,323,200 cubic feet.
1 inch deep on 1 square mile equals 0.0737 second-foot per year.
1 foot equals 0.3048 meter.
1 mile equals 1.60935 kilometers.
1 acre equals 0.4047 hectare.
1 acre equals 43,560 square feet.
1 acre equals 209 feet square, nearly.
1 square mile equals 2.59 square kilometers.
1 cubic foot equals 0.0283 cubic meter.
1 cubic foot equals 7.48 gallons.
1 cubic foot of water weighs 62.5 pounds.
1 cubic meter per minute equals 0.5886 second-foot.
1 horse-power equals 550 foot-pounds per second.
1 horse-power equals 76 kilogram-meters per second.
1 horse-power equals 746 watts.
1 horse-power equals 1 second-foot falling 8.80 feet.
1 1/3 horse-power equals about 1 kilowatt.

To calculate water-power quickly: $\frac{\text{Sec.-ft.} \times \text{fall in feet}}{11}$ = net horse-power on water wheel realizing 80 per cent. of theoretical power.

Methods of Measurement.—The measurement of water is in practically all cases accomplished by taking the rate and time of flow and computing the amount of discharge from these factors. Where the rate of flow is constant the quantity is the rate multiplied by the time. Where the rate of flow varies from day to day or, as is often the case, from hour to hour, an account must be taken of these variations. This is done by computing the amount of discharge for short periods of time, for example, a day or an hour, and summing up these amounts over the entire period of flow. In the work of the United States Geological Survey the amount of discharge for each day is used as a basis for determining the mean monthly or yearly discharge.

The measurement of rate of flow or stream measurement as it is usually called is based primarily upon measurements of the cross-sectional area and mean velocity through the measured section. In some cases, more especially on small streams or in irrigation or supply canals, measurements are made by special devices, such, for example, as wiers.

The accompanying illustration, Fig. 9, gives the ideal arrangement of a fully equipped gaging station. In the foreground is a small structure enclosing a self-registering device for keeping record of the rise and fall of the water in a small well connected with the river by a horizontal pipe, near it is a vertical gage rod to check the observations by direct reading. Devices of this kind are somewhat expensive to install and require frequent skilled attendance to adjust. In the background is a cable suspended across the river from which is hung a seat or small car from which the hydrographer can work while measuring the width, depth, and velocity of various portions of the stream. (See also Plate II, Figs. A and B, illustrating measurements from a small bridge or made by wading the stream.)

The cross-sectional area of a stream is measured by taking soundings at regular intervals, of say 5 or 10 ft., across the stream and computing the areas of each of the small sections between soundings from its width and mean depth. The sum of the small areas thus obtained is the total cross-sectional area. The velocity is determined either by means of a current meter, Plate II, Fig. C, placed in the stream, or by means of floats on the surface. The former method is susceptible of the greater accuracy and is the one generally used in stream-gaging work. In computing the discharge, account must be taken of the fact that the velocity varies in different parts of the stream and that it is necessary to divide the total cross-section into parts and compute the discharge through each part separately. This can be done readily when velocity measurements are made by means of the current meter at various points in the stream. When velocity is measured by means of floats it is generally assumed that

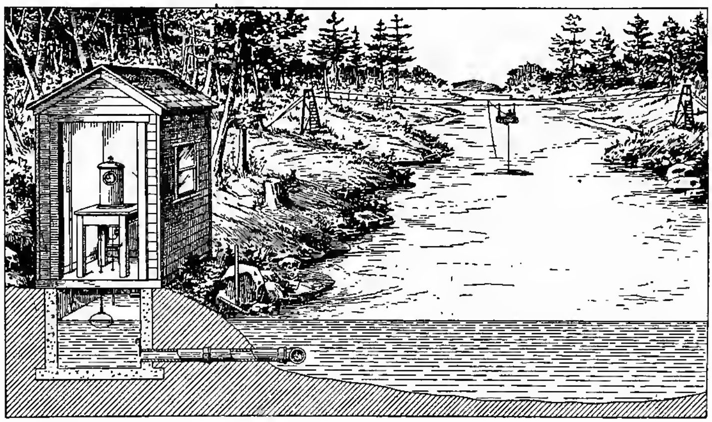


Fig. 9.—Equipment for river station, consisting of self-registering height gage, protected by small house with cable and car for convenience in velocity measurements.

the mean velocity is about 0.8 of the surface velocity. Measurements by this method are at best but rough estimates and for this reason should not be relied upon where reasonably accurate results are required.

Where conditions will permit of its installation and use, the wier is probably the most accurate method of measuring water. The conditions necessary for accurate wier measurements are such, however, that they frequently cannot be secured on streams of any considerable size. Accurate wier measurements require first, that the water above the wier be in a quiescent state and that the fall be sufficient that the surface of the water in the stream on the lower side of the wier be below the top of the wier crest. It is readily seen that these conditions are difficult to obtain on streams of any considerable size.

Results of Stream Measurement.—The results of stream measurement indicate a wide fluctuation in the quantity of flow from month to month, and from year to year. As a rule the minimum flow is when water is most needed for irrigation or during the months of July and August. It increases gradually as cooler weather comes on, continuing, however, at a relatively small amount during the winter, and reaching the flood stage during the spring months. The maximum flood follows the spring rains and melting snow occurring generally in the latter part of May or in June.

Besides the annual variations of drought and flood, there is what is sometimes called the "non-periodic" alternation of wet and dry years. For several years in succession, the floods will be high and prolonged, and the low-water season will yield a fair amount of water for irrigation, then follows one or two or sometimes three years in succession of unusual drought, when the floods are very small and the runoff not sufficient to fill the reservoirs which may have been provided. In planning irrigation works, full consideration must be given to the fact that these years of drought frequently occur in succession.

Attempts have been made to discover some rule governing the occurrence of wet and dry years. One has worked out a theory that droughts occur at intervals of seven years, while another is equally certain that an eleven-year period is more nearly correct, and still again there are advocates of a seventeen-year period. For practical purposes, there is no rule which can be depended upon other than that whatever has happened in the way of extreme drought or flood is likely to happen again, and that a series of wet years is likely to be followed by dry years, the length of duration of each of these periods being unknown.

The actual quantities of water in the principal streams month by month and year by year is given in the publications of the United States Geological Survey, these quantities being stated both in average rate of flow or cubic feet per second, and in total quantity delivered during the period in acre-feet.

Quality of Water Supply.—In addition to its quantity, the quality of a water supply to be used for irrigation should be examined. Water in its flow dissolves and carries out of the soil or rock over which it travels small quantities of mineral or alkali salts. As a result of this gradual accumulation, no stream waters are absolutely pure. Some of these salts are harmless, while others are highly injurious to plant growth.

In the arid west where the rainfall is limited, and where, as is frequently the case, the character of the rock is such that disintegration proceeds rapidly, the quantity of salts in solution is far greater than in the more humid regions of the east. Where the rocks are mostly crystalline, such as the granites, the stream waters are more nearly free from matter in solution, but where the flow is over shales, they frequently become highly charged. If waters used for irrigation contain any considerable quantity of salts in solution, there is danger of the soil becoming sufficiently impregnated to render it unfit for growing crops. This is especially the case if the soils themselves previous to irrigation contain a small amount of these harmful soluble salts.

There is no hard and fast rule as to the amount of soluble salts or alkali required to render water unsafe for irrigation purposes. This will depend upon the character of the salts, the natural conditions of the soil, the amount of water used in irrigation and the efficiency of underground drainage to prevent alkali accumulation on the surface. Few of the natural stream waters are unfit for irrigation purposes if proper precautions are taken in their use, and the lands to which they are applied are not already strongly charged with alkali. It is important to know the quality of waters, not for the purpose of condemning them but to insure their proper use.

It is frequently stated that one-tenth of 1 per cent. of soluble salts, or 100 parts of salts in 100,000 of water, is the limit of safety in irrigation waters. There are, however, instances where water containing two or three times this amount have been used without notable injury. On the other hand, waters containing less than half this amount when carelessly used have been known to injure large areas. In passing upon the quality of irrigation waters the character of the soluble salts they contain and the conditions under which they are to be used must be considered.

Amount of Water Required for Irrigation.—The amount of water which is required for successful production of crops is dependent upon the climate, soil, and kind and number of crops grown. As a rule, where water is plentiful, too much is applied to the land, especially by unskilled irrigators. The most skillful irrigator obtains the best results with the smallest amount of water. Thorough cultivation rather than excess use of water is the secret of success and the man who attempts to save labor in cultivating by putting on additional water will usually reduce the crop production and endanger his own and possibly also his neighbor's land.

Roughly stated, the amount of water required for successful irrigation varies from 1 to 3 acre-feet per acre per annum, or an amount sufficient to cover the land from 1 to 3 ft. in depth. In some sections of extreme aridity, where climatic conditions are such that crops grow during practically the entire year, this latter amount may be exceeded.

Heavy soils through which water percolates but slowly require, as a rule, less water than the more porous soils. These soils, however, require thorough cultivation to keep them in proper condition to absorb and hold the water which is applied to them. Under drought conditions, excellent crops have been raised and orchards caused to produce heavily with water carefully applied at the rate of only 1 or 1 1/2 acre-feet per acre per annum.

CHAPTER IV

DESIGN AND CONSTRUCTION OF CANALS

Capacity.—The capacity of a canal at any given point is the amount of water which will pass that point under normal conditions. In preparing plans for construction or enlargement it is necessary to know the agricultural area which the canal is to serve and the duty of water for which provisions must be made during the period of greatest irrigation requirement. In considering the total annual demand for water it is advisable to divide the requirements into months or shorter periods covering the entire irrigation season. Where data are not at hand to determine the actual amount of water required for maximum irrigation during any one month, various assumptions must be made and these estimates should be sufficiently liberal to provide for all future emergencies. If, for example, it is known that during an irrigation season of say six months in length, 30 in. in depth or 2 1/2 acre-feet per acre is required, it is probably safe to assume at least 40 per cent. in excess of this average amount, or a depth of 7 1/2 inches, may be required in a single month during the period of greatest irrigation.

Having arrived at the amount of water needed in the month of maximum demand the capacity of canal is found by multiplying the depth in feet of water required by the total number of acres to be supplied and dividing by the number of days in the month. This will give the number of acre-feet required daily, which may be reduced to second-feet by again dividing by 1.98, since 1 second-foot continuous flow for twenty-four hours equals 1.98 acre-feet.

The above is satisfactory for the design of main canals or large laterals where a practically continuous flow can be maintained from day to day. In the design of smaller canals or laterals, intended to serve but a small area, account must be taken of the fact that such canals may not be in continuous use. Provision must be made for delivering the required amount of water during the period of time that irrigation will probably be carried on from such canal. For example, a canal with a carrying capacity of 10 cu. ft. per second will deliver approximately 20 acre-feet per day, or 600 acre-feet per month. Such a canal with a maximum duty of water of 1/2 acre-foot per month is capable, theoretically, of irrigating 1,200 acres. It is probable, however, that the irrigation of a tract of this size for economic results will not require continuous irrigation, but that irrigation may be carried over the entire area in a period of from ten to fifteen days and no further application of water might be required for an equal period of time.

In fixing the capacity of a canal it is necessary to take account of the actual time that the canal is to be in operation and to provide for delivering the amount of water required during this period. Account must also be taken of probable losses by seepage and evaporation. The amount of these will depend upon the length of the canal, the nature of material, and climatic conditions. No definite rules can be laid down for their determination. Where data are at hand relative to seepage and evaporation losses these can be determined. Where such data are not at hand, estimates for them must be made. The capacity of a canal should be sufficient to provide for the net quantity of water required on the land in addition to the evaporation and seepage losses which are expected.

A convenient method of determining the capacity of a canal required for a given area is to first find the area which will be served by a continuous flow of 1 cu. ft. of water per second, which may be computed as follows:

Let a = area

d = maximum duty of water, that is, the depth required on the land for a given period of time

t = number of days in the period considered

p = percentage of loss by seepage and evaporation from the canal

Then

$$43{,}560\, ad = 86{,}400\, t(1.00\text{-}p)$$

or

$$a = \frac{86{,}400\, t(1.00\text{-}\mathrm{p})}{43{,}560\, d} = \frac{1.98\, t(1.00 - p)}{d}$$

If we assume the duty of water for a period of thirty days to be 0.6 ft. on the land and the loss by seepage and evaporation in the canal to be 10 per cent. of the total flow,

$$a = \frac{1.98 \times 30 \times 0.90}{0.6} = 79.1 \text{ acres}$$

Location of Canals.—Under the term "location" of a canal is included its relation to the source of supply, the points of delivery and all other natural or cultural conditions. In locating canals there are to be considered, among other items, (a) economy of construction and maintenance; (b) safety against possible breaks; (c) the maximum amount of land that can be irrigated under the system. Preliminary surveys, sufficient to determine a close approximation to the area to be watered must first be made. With this data and an assumed duty of water, the capacity of the canal can be determined. The next step is to design a typical section of canal and fix its slope. The various questions to be considered in this design are treated in a later paragraph, so that for the present it is sufficient to assume as fixed the cross-section of the canal and banks and the grade upon which the location is to be made.

For economic construction a canal should be so located that the excavations will equal the embankments, with a reasonable allowance, say about 10 per cent. for shrinkage. The depth of cut necessary for this is defined as the normal or economic cut. Before starting the actual work of location in the field the economic cut for level ground and side slopes of various degrees should be computed, for the ready reference of the engineer in charge of the location. Data of this kind are valuable for use in the field in determining the location for minimum cutting, which is one of the important factors in location.

Besides the minimum amount of excavation it is necessary to consider other factors. On sloping ground it is often necessary to excavate more material than is required for banks in order to put the waterway sufficiently in cut to insure safety. In locating along a slope broken by long narrow ridges it is frequently a matter of economy and good engineering on account of savings in length and in the elevation of water surface, to cut through the ridges rather than attempt to go around them on approximately the contour of the canal. The same remarks apply equally to the crossing of long and narrow depressions or draws, where the amount of material excavated is not sufficient and material has to be hauled from the adjacent ridges or taken from borrow pits to form the banks. It is frequently advisable to locate two or more alternate lines and make preliminary estimates of cost before the final location is determined.

Where fills are contemplated careful attention should be given the location on account of the great danger of breaks and of increased cost of maintenance. In locating the larger main canals especially, the question of safety should be given first consideration. It must be remembered that the extra cost of maintenance of a canal on a treacherous location, while an important factor, is of less importance than the possible losses of crops by the failure of the canal during that period of an irrigation season when water is most needed. This is notably true in extreme arid regions where the application of water is an absolute necessity for agricultural operations.

Alignment.—The accurate alignment of a canal is of secondary importance to economic and safe location. The elimination of sharp turns and reduction of curvature is desirable in order to reduce the length and to guard against erosion, which sometimes occurs on short curves. The requirements of alignment presented in the location of a canal are less rigid than in railroad work. There are, however, certain matters which should be given consideration. At the end of long tangents, where wave action may prove considerable, as is the case in large canals, the curves should be made as gentle as possible in order to avoid washing of banks. Especial precautions should be taken if the exposed bank is in fill. Shorter curves may be used with the same degree of safety if the curve is thrown into the slope, as is the case when passing around the head of a draw, than when the curve is thrown outward as in passing around the point of a ridge. This is on account of the greater velocity and increased tendency to erosion on the outside of the curves.

The precise amount of resistance which a curve offers to the flow of water in open channels has not been definitely determined. It is believed, however, for velocities of flow which are safe for earthen canals that a curve in the center line whose radius is two and one-half times the bottom width of the canal may be used without any appreciable effect on the average rate of flow. The above rule is considered by some engineers as a safe one to apply in determining the alignment of canals. There are, however, numerous examples where this curvature is exceeded and satisfactory results obtained, especially where a canal is principally in cut, so that erosion does not have the effect of weakening the banks.

Cross-section.—The selection of a cross-section for a canal is one involving economy of construction and maintenance as well as security against failures which may prove disastrous to an irrigation system. It requires the consideration of the theory of flow of water in channels and the exercise of engineering judgment. From the standpoint of theory alone it would appear the section which will (a) carry the necessary amount of water; (b) conserve grade so as to cover the greatest possible area and, (c) require the least amount of excavation in its construction, is the one which should be selected. For a canal of given slope and fixed area of cross-section the greatest velocity will be attained by selecting the section with the maximum hydraulic radius. From this it follows that such a section will require less grade for the same capacity than any other of equal area. It can be shown that a circular or semi-circular section has the largest hydraulic radius for a given area. It can also be shown for rectangular and trapezoidal sections that when the width of surface is equal to the sum of the two side slopes and the hydraulic radius is equal to one-half of the depth of water the hydraulic radius is a maximum. The most advantageous rectangular section is one whose top width is equal to twice the depth. For trapezoidal sections certain fixed relations between width and depth of water, depending upon the steepness of side slopes, must be maintained in order to get a maximum hydraulic radius. These relations, for a few of the more common slopes in use, are as follows:

Slopes 1/2 hor. to 1 ver.—surface width = 2.24 × depth.
Slopes 1 hor. to 1 ver.—surface width = 2.83 × depth.
Slopes 1 1/2 hor. to 1 ver.—surface width = 3.60 × depth.
Slopes 2 hor. to 1 ver.—surface width = 4.47 × depth.

These sections, while theoretically the most advantageous, are generally not the most practical, on account of the excessive depths required for canals of large cross-sectional areas. The accompanying illustration indicates sections on which canals have been built under ordinary conditions of nearly level or slightly sloping ground.

In building earthen canals it is necessary, for the sake of economy, to utilize the embankments to form a part of the waterway. In other words, the water must be held in part against the bank in order to reduce seepage and minimize the danger of breaks. It is advisable also to limit the pressure or head against artificial banks. Generally a wide and shallow canal is less liable to cause trouble due to seepage than a narrow and deep one. The shallow canal, on the other hand, for the same area of cross-section, requires more grade to give it the same carrying capacity than a narrow and deep canal. The relative advantages of various types of section has been the subject of considerable discussion among irrigation engineers. The arguments presented, while of value in considering an individual case, do not lead to general conclusions. The narrow and deep section, while generally requiring a less amount of excavation for a given capacity and grade, may prove the more expensive of construction on account of the character of excavation encountered, and difficulty of removing materials from a greater depth. A wide and shallow canal on side hills has the disadvantage of requiring large amounts of excavation on the upper side, and does not permit of keeping the waterway well within the excavated portion of the channel on the lower side without considerable cost.

No fixed rules for the selection of a canal section can be formulated, but each particular case must be treated with due regard to safety and economy of construction. In practice it is necessary to consider the maximum depth of water a canal can safely carry, the height of water surface above the natural ground surface, and the depth to which excavations can be made economically. In large canals these factors will ordinarily control in fixing the depth of section and the area required for necessary capacity will determine the width. For small canals, where the depth is not great and where grade is sometimes an important factor, consideration should be given to the section of greatest hydraulic radius.

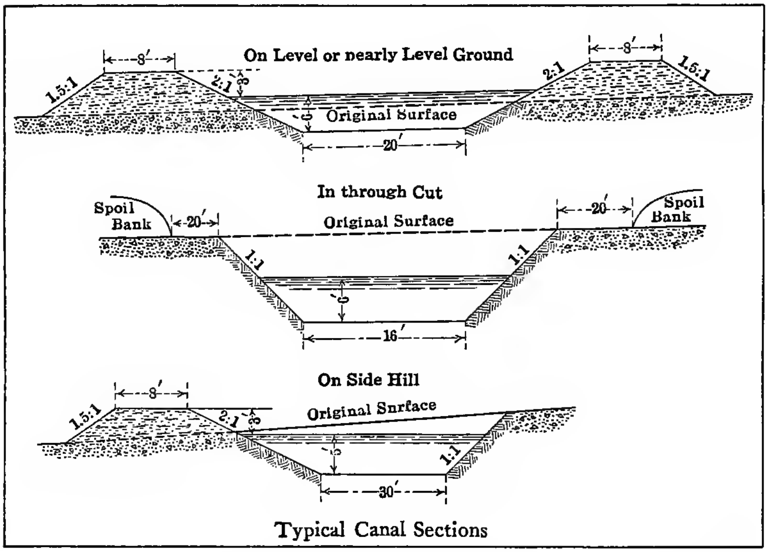


FIG. 10.—Typical cross-section of irrigation canals in level or sloping ground and in relatively firm material.

Canals on comparatively level ground are sometimes constructed by placing the embankment back a few feet from the upper slope of the excavation, thus forming a berm. The effect of this is to increase the cross-sectional area without increasing the amount of excavation. On account of the comparatively shallow water near the embankments, the velocities in this portion of the section are reduced and there is less tendency to erosion of the banks. The section of a canal constructed with a berm, except over very flat country, is irregular in area, the water being restricted to a narrow channel where cuts are deep and allowed to widen out where the cutting is shallow. Where it is necessary to operate canals at varying capacities the berms are alternately wet and dry, and conditions are favorable for a growth of weeds and grass. It is believed that in general, berms are a disadvantage rather than an advantage and that the most satisfactory results are attained by the use of a uniform cross-section with side slopes sufficiently flat to prevent erosion and a gradual sloughing into the canal.

Slopes and Width of Banks.—The degree of steepness of the slopes to which canal banks should be constructed depends largely upon the character of materials. As has been shown in the previous paragraph, the steeper the inner side of the banks, the less the amount of excavation required in order to form a channel of given capacity. This is more marked in deep cuts, where a large part of the excavation is above the water section. It follows then for deep cuts that the slopes of banks should be made as steep as the material will stand with safety. This varies from about 1/2 horizontal to 1 vertical for rock to about 3 horizontal to 1 vertical for ordinary light earth. In some cases slopes may be made steeper than 1/2 to 1; in general, however, slopes steeper than this except in very firm rock have a tendency to slough, due to weathering, which results in a gradual filling of the channel.

For earthen slopes, material is seldom encountered that will stand on a greater slope than 1 1/2 to 1. In that portion of the channel forming the waterway, there is a tendency for the sides to be gradually eroded or eaten away by the action of the water. The greatest erosion usually takes place a short distance below the surface of the water and from this point the cutting gradually decreases toward the bottom. The effect of this erosion is to form a rounded channel in which the sharp angle of intersection between sides and bottom is eliminated. The general result is a flattening of the sides of the entire bank, due to erosion and the weathering of the material above where the erosion takes place. Banks con-

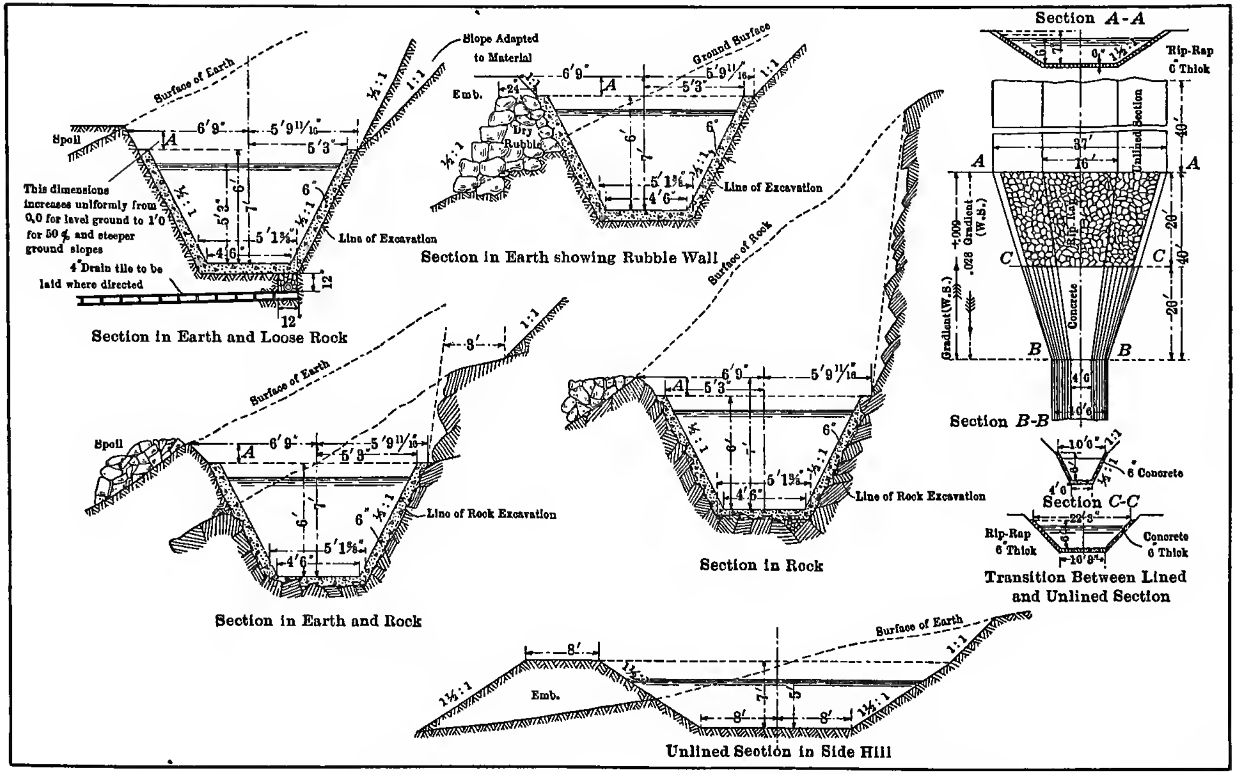


FIG. 11.—Sections of lined canal on steep rocky slopes, Yakima Project, Washington.

structed with 1 1/2 to 1 slopes after a few years are found to have become 2 to 1 or even flatter. When it is desired to maintain a roadway on the top of an embankment it is necessary to construct it somewhat wider than will be eventually required on account of the reduction in width which follows the flattening of the slopes. Where the embankments are constructed with flat slopes the tendency for the top width to decrease is lessened. On the outer slopes of banks there is a less tendency to flattening, partly due to absence of water against them and the consequent effects of erosion and softening of the material. In very light materials, however, wind action may have an important effect in reducing the outer slope. One of the dangers in too steep outer slopes, especially in new canals, is the tendency to slough or run when the bank becomes saturated. This danger may become serious in banks of considerable height built of light permeable material. The top width of banks required and its height above the water surface in the canal are questions to be decided in each particular case and will depend upon the depth of water and character of the materials of which the banks are constructed. For the larger and more important canals it is believed that the height of banks above the maximum water surface should not be less than 3 ft. and the top width not less than 8 or 10 ft. Where a roadway is maintained on the top of banks this width should be increased.

Material for Banks.—Ordinarily there is but little choice of materials for forming the waterway for canals, since in most cases it is necessary, to keep the cost within reasonable limits, to use for this purpose the natural materials found on the canal location. It frequently occurs that canals are required to be constructed through soils or rocks which are exceedingly pervious to water, and the engineer is called upon to decide whether or not a channel can be constructed that will be reasonably water tight. This question involves not only that part of the waterway formed above the natural ground surface by means of artificial banks but applies to that portion of the channel which is in cut also especially on sidehill work. Clay is perhaps the least permeable of the various materials through which canals are built, while coarse sand or gravel offer least resistance to the passage of water. The question of permeability of earth depends upon the amount of fine material which it contains. Sand or gravels are composed of solid particles of appreciable dimensions, voids of notable size occurring between the particles. The same is also true in broken or shattered rock formation, where the spaces between the rock are not filled with earth or other fine material. Clay, on the other hand, composed of fine particles, has correspondingly small voids, so small as not to permit the ready passage of water.

In addition to the question of permeability, the character of the materials should be taken into account in fixing the cross-section, the slopes of banks and the velocities which can safely be maintained. Where the quantity of material capable of making a water-tight bank is limited, a segregation of materials is sometimes necessary, the water-tight material being placed either on the inner face or in the form of a core in the center of the bank. In general it is more economic to place this material on the inner slope of the canal than in the center of the bank. In this position, however, there is some danger of the face of the slopes being carried away by erosion, or by a breaking down into the canal, thus leaving the porous substrata exposed.

The treatment of side slopes applies equally well to the bottom of canals in porous materials. Soils and loams which contain a considerable amount of vegetable matter usually form tight banks, but, on account of the material being comparatively light, require relatively flat slopes. Sufficient clay mixed with sand or gravel to fill up the pores and give it solidity makes a good material for banks. In constructing canals where different materials are encountered in the excavations, it is good practice to specify that the coarse materials shall be placed in the outer and the finer materials in the inner portion of the banks.

Grades and Velocities.—The grades of canals are fixed in many cases by practical rather than by theoretical considerations. Where the grade must be kept to the minimum in order to reach the largest practicable area of irrigable land the relative elevations of the head of a canal and the lands are the controlling factors. In this case, velocity and some economy of construction of the canal is sacrificed in order to increase the irrigable area. The problem which the engineer is required to solve is to find the point of balance between the extra cost of construction and the value of the additional lands which may be irrigated. Where there is ample grade, so that the holding up of a canal is unnecessary, the problem presented is one of greatest economy of design and construction consistent with safety and economy of operation.

There are certain limitations which cannot be overlooked. If the grade of a canal is too flat and the corresponding velocity of flow too low there is a constant tendency to a filling up of the canal due to deposits of silt from waters carrying material in suspension. The growth of noxious weeds and grasses in a canal is also facilitated by reducing the velocity beyond certain limits. Where grades are too steep and velocities correspondingly high, erosion of the channel is the result.

The ideal grade for a canal is one which will neither cause erosion nor permit silt to be deposited. This condition, however, cannot be fully realized, on account of the different materials through which canals must be constructed and the varying character of the materials carried in suspension. In order to prevent erosion in canals it has been considered necessary that the velocities be kept below certain limits for different classes of materials. These limits are ordinarily stated to be from about 2 1/2 ft. per second for very light soils to from 5 to 7 ft. per second for the firmest earth materials. It is generally considered that erosion is a function of the velocity and that account need not be taken of the grades necessary to produce this velocity in canals of different sizes and shapes of section. A further consideration of the subject seems to show that erosion in a canal is a function of the grade, size and shape of the section, as well as the velocity, or, in other words, it is dependent, to a certain extent, upon the amount of energy expended by the current in overcoming the resistance of friction in the channel.

This point may be illustrated by considering two canals of similar cross-sections, but of such relative sizes that the smaller requires twice the grade as the larger to produce the same velocity of flow. It is evident that the energy expended per unit quantity of water in overcoming friction will be larger and consequently the tendency to erosion greater in the smaller or canal of steeper grade. The same principle applies to canals of equal cross-sectional areas but of such different shapes of cross-sections that more grade is required in one than the other to maintain the same velocity. The question as to how much erosion in canals is affected by increased grades, velocities remaining constant, is one upon which experimental data are lacking. Observations on large and small canals constructed in the same character of materials seem to indicate that the small canals erode under lower velocities than larger canals. Take, for example, a canal 4 ft. wide on the bottom with 1 1/2 to 1 side slopes and carrying water 3 ft. deep. The hydraulic mean radius for this canal is approximately 1.7; with a grade of 0.00125, or 6.6 ft. per mile and a value of $n=0.025$ the velocity of flow is approximately 2.90 ft. per second. Erosion under these conditions would probably take place, except in the firmest materials. A canal 40 ft. wide on the bottom with 1 1/2 to 1 side slopes and carrying water 10 ft. deep would have a hydraulic mean radius of 7.6 and with $n=0.025$ would require a grade of 0.00015, or 0.8 ft. per mile to give it the same mean velocity. The latter grades and velocity would not be considered excessive, and erosion would probably not occur in average firm soil.

Silting of channels is a subject to which comparatively little attention has been given in the United States on account of the relatively small amount of silt usually carried by irrigation canals. In India and Egypt, where large quantities of silt are taken into canals, considerable attention has been given to velocities and forms of cross-sections to prevent deposit of this material. The velocity required to prevent such deposit is dependent upon the character and fineness of the material carried. It has been the common theory that a velocity of 2 ft. per second was sufficient to prevent the deposit of silt. It is probable, however, that a careful series of observations under different conditions would show that in some cases silt would be carried by lower and in other cases deposited by higher velocities.

Mr. R. G. Kennedy, who has made extended studies and observations on silting of canals in India, advances the theory that the silt-carrying power of a canal is a function of the depth of water as well as of the velocity. From his experiments Mr. Kennedy has worked out an empirical formula showing the relation between limiting velocity at which silt will be deposited and depth of water, as follows: $V=Cd^m$ in which V = velocity at which silt begins to deposit, d the depth of water and c and m constants. The values of these constants as determined are $c=0.84$ and $m=0.64$. This theory shows that silt will be carried by a less velocity in shallow than in deep canals.

It has been found in practice that the varying of the cross-section and grade of a canal each have a tendency to produce erosion and silt deposits, and that the best results are obtained by maintaining a uniform section and slope.

The following is a table of hydraulic functions of some of the principal canals constructed by the U. S. Reclamation Service. The values given for "n" are those assumed in the design of the canals.

SECTIONS AND SLOPES OF SOME OF THE PRINCIPAL CANALS OF THE U. S. RECLAMATION SERVICE

Project	Name of canal	Size		Side slopes	Velocity	Capacity	Slope	*N*
		Bottom width	Depth					
Truckee-Carson.	Main Truckee	20	13	1½:1	2.96	1,520	0.000154	0.025
Truckee-Carson.	Main Truckee	12	13	1 :1	3.70	1,202	0.0003	0.025
Truckee-Carson.	Lateral Line AA	13	6	2 :1	2.53	380	0.0002	0.020
Truckee-Carson.	Lateral Line F	4	3	2 :1	1.65	50	0.00025	0.02
Truckee-Carson.	Lateral Line I	6	3	2 :1	1.73	62	0.0002	0.02
No. Platte	Interstate	34	10	1½:1	2.86	1,407	0.00017	0.025
No. Platte	Interstate	24.5	10	2 :1	2.94	1,220	0.00017	0.025
No. Platte	Interstate 2nd	30	9.5	½:1	2.75	908	0.00017	0.025
No. Platte	Interstate 2nd	22	8.5	1½:1	2.50	738	0.00017	0.025
Lower Yellowstone.	Main	23.5	10	1½:1	2.14	824	0.0001	0.025
Lower Yellowstone.	Main	23	8	1½:1	1.89	529	0.0001	0.025
Lower Yellowstone.	Main	15.5	6	1½:1	2.12	312	0.002	0.025
Huntley	Main	14.5	7	1½:1	2.29	401	0.0002	0.025
Huntley	Main	11	5	1½:1	2.60	240	0.0004	0.025
Huntley	Main	8	3	1½:1	2.62	98	0.0008	0.025
Huntley	Main	5	3	1½:1	2.00	56	0.00055	0.025
Huntley	Main	4	2	1½:1	1.52	21	0.00055	0.025
Uncompahgre	South	30	10	2 :1	2.5	1,248	0.000135	0.025
Uncompahgre	South	40	8.3	2 :1	2.5	1,175	0.00015	0.025
Belle Fourche	North	40	9	1 :1	3.08	1,358	0.0002	0.025
Belle Fourche	North	27	7	1½:1	2.51	659	0.0002	0.025
Belle Fourche	North	23	7	1½:1	2.45	575	0.0002	0.025
Belle Fourche	South	20	5	1 :1	2.47	307	0.0003	0.025
Belle Fourche	South	16	5	1½:1	2.36	278	0.0003	0.025
Belle Fourche	Waste Channel	50	15	1 :1	3.00	2,926	0.0001	0.025
Belle Fourche	Inlet	40	10	1 :1	3.27	1,635	0.0002	0.025
Belle Fourche	Inlet	36.6	10	1½:1	3.22	1,659	0.0002	0.025
Klamath	Main	44	11	1½:1	2.25	1,500	0.000081	0.025
Klamath	E. Branch	16	6	1½:1	1.74	261	0.000132	0.025
Umatilla	Feed	13.0	5.5	2 :1	2.19	300	0.000201	0.0225
Umatilla	Feed	11.8	5.5	1½:1	2.18	300	0.000193	0.023
St. Mary	Main	27	8	1½:1	2.70	850	0.0002	0.025
Shoshone	Garland	40	6.5	2 :1	2.91	1,000	0.00022	0.0225
Shoshone	Garland	20	9.7	2 :1	2.58	1,000	0.00016	0.025

Excavation.—Under the term "excavation" as applied to canals there is generally included all earthwork required for the construction of the canal, the formation of embankments, and such other incidental work as building approaches to culverts and bridges and the backfilling around structures.

The excavation of canals, on account of the relative magnitude of the work, is one of the most important factors in the construction of an irrigation system. The fundamental questions involved in excavation are those of cost and the determination of methods by means of which the most satisfactory and economic results can be obtained. There are also involved the measurement and classification of the materials excavated and the direction of the work in such a manner that the canal when completed will serve as a permanent waterway with a minimum loss by seepage and cost for maintenance. Excavation from canals is commonly done either by teams or some form of power excavating machinery. The advantage of either of these methods over the other depends largely upon the character of materials to be handled and the local conditions affecting the work. Where work is scattered over a considerable area, as is the case with small canals, it is ordinarily done to best advantage by means of teams and scrapers, or some form of portable excavator which can be handled by teams or traction engines as shown in Plate III.

When the work is concentrated at one point so as to require but little moving of machinery, as is the case in excavating large canals or making deep cuts, heavy excavating machinery, such, for example, as steam shovels, drag-line scrapers, or dredges are more economical and permit of better progress being made than the use of teams. The amount of work to be done must also be considered in determining the most economic and feasible method. For a small job where the cost of installing a plant forms a large proportion of the total cost of the work the unit cost by means of machinery may exceed what it would have been with a less expensive equipment, even though the latter is less efficient in character, while for a large job the cost of installation of the more expensive and efficient machinery could have been distributed over a large amount of work and the unit costs correspondingly decreased. (See Plate IV, Figs. A and B.)

The distance which material has to be moved is also important in determining the method to be used. For team work, where the haul does not exceed from 100 to 200 ft. Fresno scrapers, drawn by four horses, have been found to be the most efficient, while for greater distances preference is given to other types, as for example, the wheel scraper. The advantage of the latter is that the hauling which consumes the greater part of the time can be done with a less number of animals than is required by any form of drag scraper. It is customary in long hauls to use extra animals for loading and detach them when the loading is completed, allowing one team to transport the load to its destination. (See Plate II.)

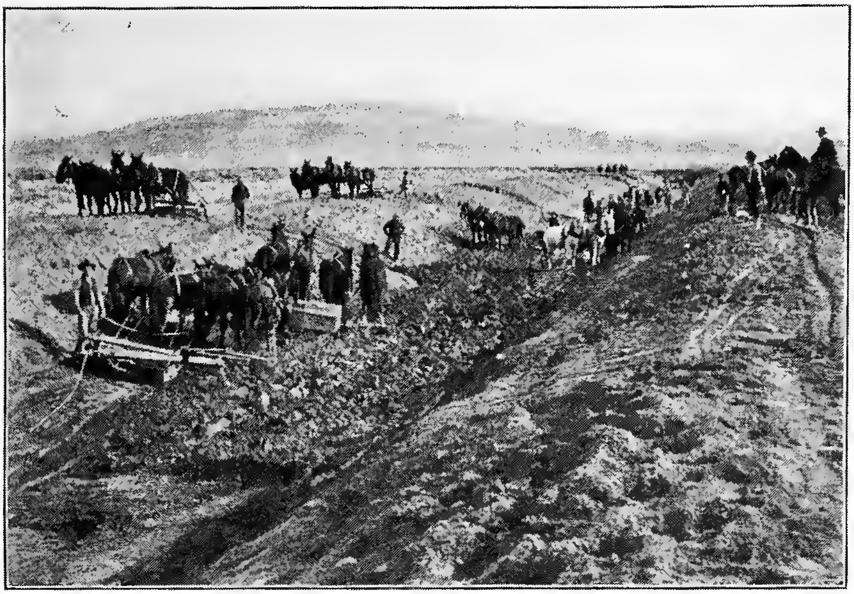


FIG. A.—Constructing canal in earth by means of four-horse Fresno scrapers. Minidoka Project, Idaho.

FIG. B.—Throwing up small laterals by means of four-horse road machine. Huntley Project, Mont.

FIG. C.—Excavating canal by use of excavator with belt conveyor, drawn by traction engine. Belle Fourche Project, So. Dak.

FIG. D.—Finished canal with both upper and lower banks. Lower Yellowstone Project, Mont.

In building embankments team work has an advantage over other methods on account of the consolidation of the embankments due to the tramping of the animals. When embankments to hold water are built by other methods it is necessary to adopt some means of compacting the earth. The most common way of doing this is by means of rolling or tamping. On account of the difficulty of rolling small banks teams for this class of work are usually favored.

It must be remembered that each particular job of excavation differs in some particulars at least from other jobs of similar work, and that methods which have proven entirely satisfactory in one case may be wholly unsuited to another job. For this reason it is impossible to say in general that one method is superior to another. In estimating the cost of work by a particular method the safest plan is to compare it with the cost of similar work elsewhere, allowance being made for difference in local conditions. Results obtained in this manner are likely to prove far more satisfactory than those based upon theoretical considerations.

As a basis for estimates, and the fixing of prices for handling different kinds of materials, it is customary to divide excavation into classes. One method of classifying is by natural designations, such, for example, as earth, hard pan, loose rock, solid rock and similar terms. A second method is to classify the materials according to the way in which they can be handled, as, for example, materials which can be plowed, and those which require drilling and blasting. Both methods are to a certain degree inexact and leave a great deal to the judgment of the engineer.

In attempting to use the method first named it is sometimes impossible to draw a sharp line of demarcation between the different materials. The distinction between earth and hard pan or even between earth and rock is not always easily determined on account of the blending of one class of material into the other. It sometimes happens that proper classification according to such designations can be made only by a trained geologist. Such geological classification may have little practical value as a measure of the amount of work required in excavation. Some material properly defined as earth may be more difficult and expensive to remove than other material which may be properly termed rock.

The second method of classification according to some assumed mechanical operation avoids the use of vague terms, and may depend more nearly upon the amount of work, and the resultant cost thereof, which will be required. For example, material which can be plowed can ordinarily be handled with less effort and at a lower cost than material which has to be loosened by blasting or other expensive operations. This method of basing classification upon well-known and clearly defined operations for loosening or handling materials has been found the more satisfactory. Differences of opinion relative to such a classification can ordinarily be tested by simple operations on the work, thus avoiding definitions which may depend upon fine technicalities.

Specifications for Excavation.—The construction of canals, whether to be done by contract or by hired labor which is directly under the control of the engineer, should be done in accordance with definite plans and specifications. For contract work specifications are necessary to define exactly what is covered by the contract and avoid all misunderstanding, and where the work is being performed directly by hired force they are of nearly equal importance as a guide to the superintendents and others in carrying out the work. The specifications with the plans of the work should be sufficiently complete to answer all ordinary questions relative to the operations such as methods of measurement, payment, classification of materials, and how the work shall be handled. The following specifications, modified when necessary to meet special conditions, are in use by the U. S. Reclamation Service:

(a) *Classification.*—All material required to be excavated in connection with the construction of the canal will be measured in excavation and classified for payment as follows:

Class 1. All material that is loose and can be handled with scrapers and all material that can be plowed by a six-horse team, each animal weighing not less than 1,400 lb., attached to a suitable plow, all well handled by at least three men; also all loose rocks in pieces not exceeding 2 cu. ft. in volume occurring in loose material or in material that can be thus plowed.

Class 2. All material not included in Classes 1 and 3.

Class 3. All rock in place that cannot be removed without the use of powder and all detached masses of rock exceeding 10 cu. ft. in volume.

(b) *Canal Section.*—The canal and embankment sections are shown in the drawings, but the undetermined stability of the material that will form the canal banks may make it necessary during the progress of the work to vary the slopes and the dimension dependent thereon. Variations of this character will not entitle the contractor to pay at any other rates than those named in the contract. The canal shall be excavated to the full depth and width required and must be finished true to line and grade in a workman-like manner. Earth slopes shall be neatly finished with slip scrapers or other suitable appliances. Rock bottoms and banks must show no points of rock projecting more than 0.3 ft. in the prescribed section. Above the water line the rock will be allowed to stand at its steepest safe angle, and no finishing will be required beyond removal of rock masses that are loose and liable to fall.

(c) *Material to be Laid Aside.*—Whenever directed by the engineer materials found in the excavations such as sand, gravel or stone that are suitable for use in structures or that are otherwise required for special purposes shall be preserved and laid aside in some convenient place designated by him.

(d) *Material for Canal Embankments.*—All suitable material excavated within the prescribed canal lines will be available for embankment construction. So much thereof as may be needed shall be placed in the embankment where directed by the engineer. Where this source of material is inadequate additional material may be obtained from borrow pits whose location will be subject to the approval of the engineer. Unless the engineer gives the contractor specific written orders to excavate other than Class 1 material from borrow pits for embankment construction all material obtained from this source for such purpose will be paid for at the unit price bid for Class 1 regardless of its actual character.

(e) *Construction of Embankments.*—The ground under all embankments that are to sustain water pressure shall be cleared of brush, trees and roots. The foundation surface shall be well plowed. Should the engineer direct that unsuitable material be excavated and removed from the site of the embankment the material thus excavated will be paid for as excavation. All material deposited in embankments that are to sustain water pressure shall be thoroughly compacted. The compacting must be equivalent to that obtained by trampling of well-distributed scraper teams depositing the material in layers that are 6 in. thick when compacted.

(f) *Runways.*—Runways shall not be cut into canal excavation slopes below the proposed water level.

(g) *Blasting.*—Any blasting that would injure the work will not be permitted. If the slopes are shattered or broken by blasting, such places shall be excavated to firm material, and the holes thus made shall be filled to grade or slopes with such material and in such manner as the engineer may designate, all at the expense of the contractor.

(h) *Excess Excavation.*—Material excavated for the canal in excess of that required for canal embankments shall be used for the widening of the embankments as may be directed by the engineer. Material taken from cuts that is not suitable for embankment construction and other material not required for embankments or embankment widening may be wasted on the right-of-way owned by the United States, provided it is not deposited in drainage channels nor within 25 ft. of the edge of the canal cut.

(i) *Overhaul.*—In hauling excavated material required for embankments or other useful purposes or for laying aside for subsequent use, 200 ft. will be considered the limit of free haul and any haul in excess of this distance will be termed overhaul. Whenever the engineer requires such material to be hauled more than 200 ft., the contractor will be paid for overhaul at the rate of one and one-half cents per cubic yard per 100 ft. for the haul in excess of 200 ft. No overhaul of material wasted will be paid for.

(j) *Measurement and Payment.*—Measurement will be made to the neat lines of the excavation as shown on drawings or staked out by the engineer. Payment for excavation will be made at the unit price bid therefor which shall include the cost of all labor material and supplies incident to excavating and placing the material in embankments, preparing surface, spreading, rolling, tamping, etc., required to complete the work in accordance with the specifications.

Protection Against Seepage in Canals.—The losses of water in transmission in a canal system, especially one recently constructed, form a notable proportion of the amount of water received into the canal. Careful observations and studies should be made of these losses in order to ascertain where they are taking place and to take measures for their correction, not merely to prevent the loss of the water which is valuable in itself, but to keep this seepage water from ruining lands in the vicinity. The amount of these losses is illustrated by the accompanying figure which gives for comparison the total diversions from the river in each case, and the proportion of this which is lost in transmission.

The accompanying figure (12) gives for the months of April to September or October the quantity of water which was received into the canal, this being indicated by the vertical spaces and the quantity which is lost in transit. This is classified in most cases into the losses in the main canal and those in the lateral system.

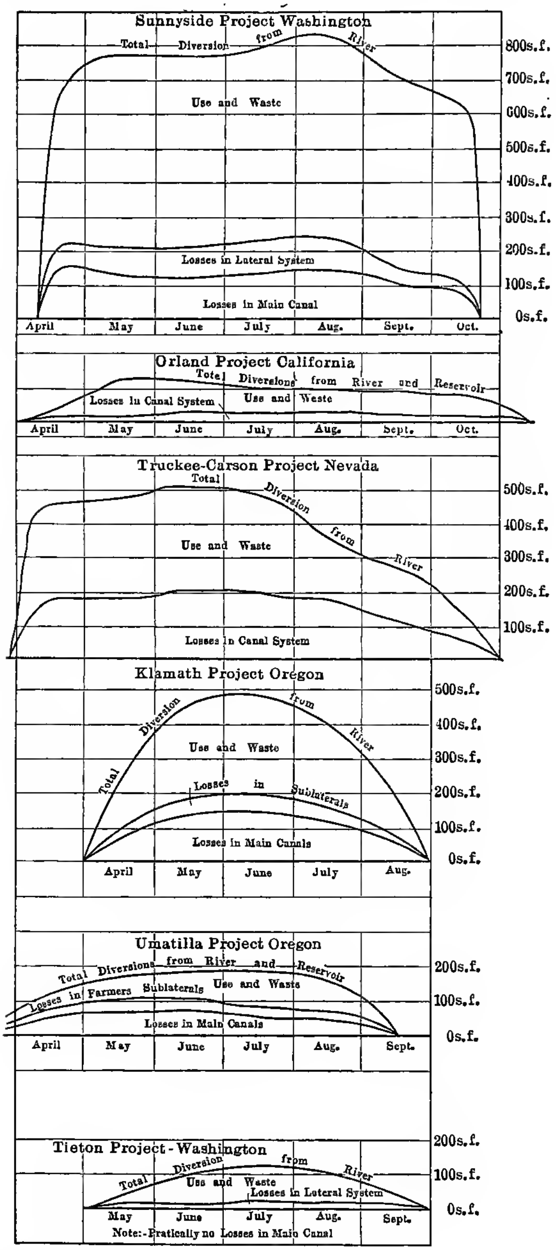


FIG. 12.—Diagram illustrating relative quantities of water used, and lost in laterals and in main canals of various projects during the crop season of 1911.

It is to be noted that in general the losses are in proportion to the quantity diverted, although theoretically at least the losses during the early part of the season should be greater in proportion to those later on.

Where it is necessary to use unsatisfactory material for the construction of canal banks, or where canals are excavated in loose or porous material, special precautions have to be taken against loss of water by seepage. Seepage from canals may be either through the sides and bottom under the artificial banks, or through the embankments themselves. Where it is of the first form it frequently penetrates to some depth in the natural material and comes to the surface at a considerable distance from the canal. Seepage of this kind is the most difficult to prevent. It can sometimes be avoided by cutting a deep trench underneath the canal embankment and filling it with puddle or other impervious material. Where this method is employed it is necessary to carry the core down to impervious material which can frequently be done on side-hill work.

Another method of preventing seepage is to cover the slopes and bottom of the canal with fine material, such as soil or loam, which, when acted upon by the water is carried into the interstices of the material below in time forming a water-tight film along the surface.

The remedies for seepage through artificial banks are practically the same as those above mentioned, *i.e.*, by constructing a core of puddle or other impervious material in the center of the bank, or by lining the inner slope with soil or other fine material.

Where a canal is lined to prevent seepage, care must be taken in future maintenance and cleaning of the canal to avoid removing or breaking into this thin layer of water-tight material.

In the construction of canals much can be done to prevent seepage through the banks by requiring that the coarse material be placed on the outer portion and the finer material on the inner side of the banks. In the construction of canals in cold climates, especial care should be taken to see that material is not deposited while the material or the embankment is frozen. When in a frozen condition, material, especially if it be moist, occupies a greater space than after it is thawed, and in the process of thawing is likely to leave small openings through which water can escape.

Another method for preventing seepage which is sometimes resorted to is by lining the canal either with masonry, plaster or lumber.

On one of the Reclamation Service canals, where it was necessary

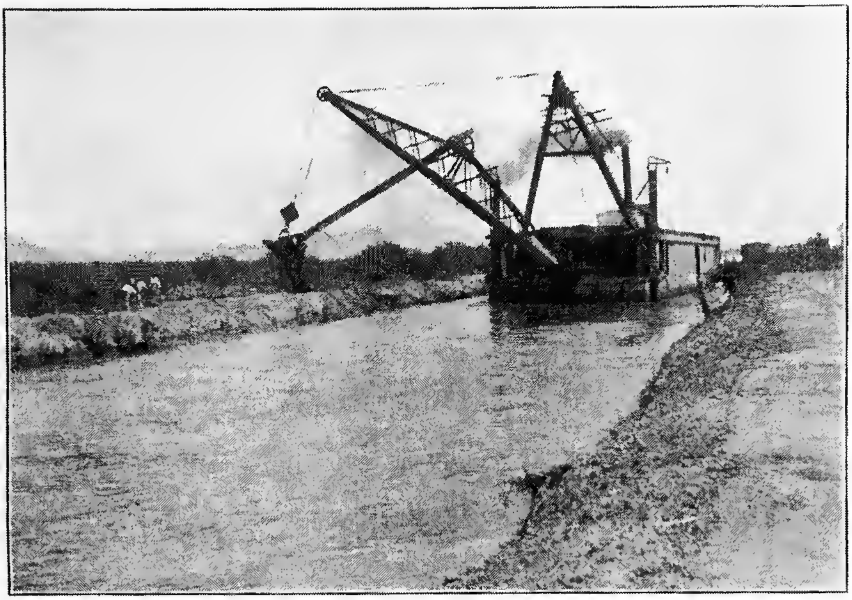


FIG. A.—Enlarging canal by means of floating dipper dredge. Salt River Project, Ariz.

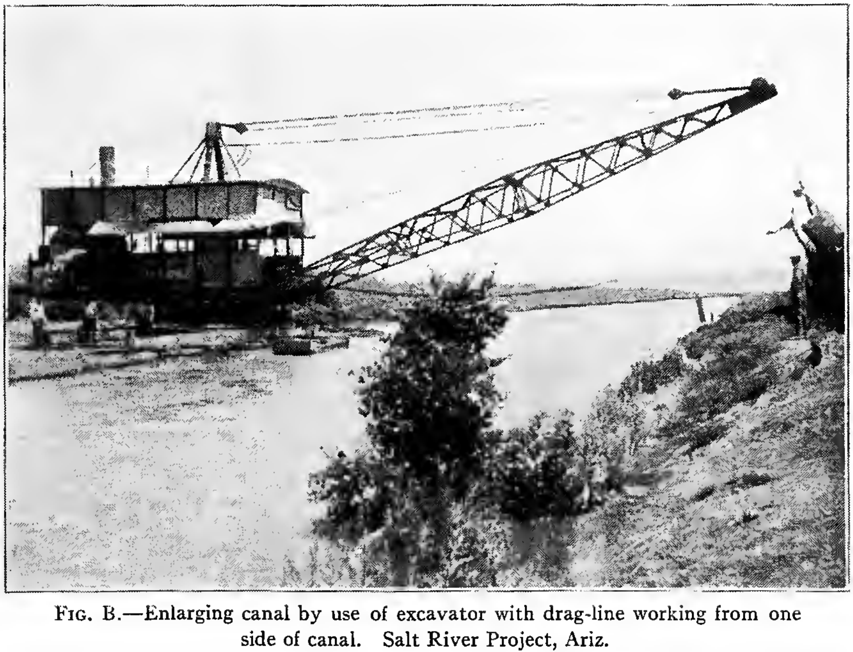


FIG. B.—Enlarging canal by use of excavator with drag-line working from one side of canal. Salt River Project, Ariz.

FIG. C.—Lining canal with concrete to increase the capacity, and reduce the seepage. Boise Project, Idaho.

FIG. D.—Concrete lined canal in shattered rock, carrying water of Truckee River to Carson River. Truckee-Carson Project, Nev.

to carry water through a canal constructed on a large fill, a temporary lining of lumber was constructed to be used until the embankment should become thoroughly settled. The future plans provide that when such settlement has taken place and the lining must be renewed it will be replaced by some form of permanent material.

Seepage sometimes results from erosion of banks by which the finer material along the surface is carried away. This is most likely to occur on the outer slope around curves.

Lined Canals.—In the construction of canals a permanent lining of concrete is frequently used. The purpose of such a lining is twofold; first, to prevent seepage where a canal is constructed in porous material; and second, to increase the velocity and thus reduce the section of the canal where deep cutting is required. If, for example, a canal is to be constructed to a depth two or three times that of the depth of the water it is frequently cheaper to excavate a smaller section and line the lower wetted portion than to excavate a canal having the required capacity in earth section. Where concrete lining is used, it is economical to make the side slopes as steep as possible. As shown on page 39, the most advantageous section theoretically is one with vertical slopes. This, however, is impracticable. It frequently happens, however, in deep cuts that material will stand on as steep slopes as 1/2 horizontal to 1 vertical, which is a section very commonly used in lined canals. In placing the lining in canals with slopes as great as 1/2 to 1, it is ordinarily necessary to use forms on the inner slope, filling in the concrete between the forms and the earth or rock banks. Where the excavation is taken out beyond the neat lines this space can be backfilled with loose rock. In placing lining on slopes 1 horizontal to 1 vertical, or flatter, it is possible to do the work without the use of forms. (See Plate IV, Fig. 6.)

Canal linings are usually constructed in slabs of from 10 ft. or more in width built in alternate sections so as to provide expansion joints and prevent temperature cracks. Paper, or a thin painting of oil, is sometimes applied to the edge of the slabs to prevent the concrete bonding. This protection, however, is ordinarily unnecessary if the concrete in the first slabs is allowed to set before the second is put in. The thickness of concrete used for a permanent canal lining varies from 3 to 6 in., depending upon the steepness of the slopes, the nature of the material, and climatic conditions. Freezing has a tendency to loosen the lining from the banks by the expansion due to crystallization of the small amount of water in the earth. In a cold climate, where freezing is likely to penetrate the lining, the customary thickness for conditions of this kind is about 6 in. In climates where frost is not prevalent a less thickness is sufficient.

Linings sometimes fail on account of the pressure exerted by water which collects behind them. This can be relieved by putting weep holes through the bottom of the lining at frequent intervals. The construction of weep holes is also an additional protection against frosts as they keep the material back of the lining drained and reduce the amount of expansion when freezing occurs.

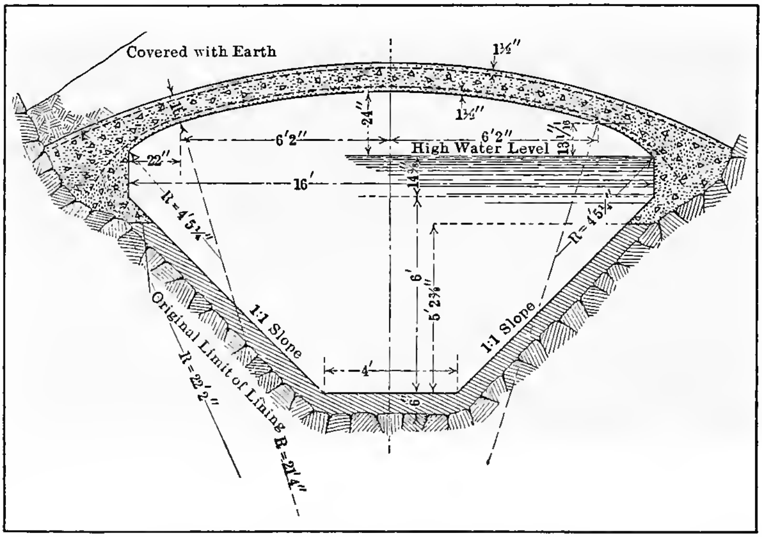


FIG. 13.—Cement lined canal with reenforced concrete arch cover later added to catch the loose, sliding débris from steep hill slopes, Strawberry Valley Project, Utah.

Roadways on Banks.—Roadways on the banks of canals have certain advantages, in that they permit of easy access to the canal for operation and maintenance purposes. In highly cultivated areas, where land is valuable, there is a saving of the land that would otherwise be required in the location of highways. There is also a certain gain due to the compacting effect of travel on the banks. This latter, however, is of little value except on new canals.

The disadvantages of roadways constructed on canal banks are that with certain materials the traffic has a tendency during the dry season to break up the surface layers into dust, rapidly carried away by the winds. There is a tendency also to wearing down of the banks into ruts which, during the rainy season, become filled with water which finally breaks over the banks and causes erosion of the slopes.

The practicability of constructing roadways on the banks of canals in general depends upon the local conditions, all of which must be taken into account in determining the proper course to pursue. Where roadways are constructed on banks it is necessary to make the top width somewhat greater than would be required if such roadways were not built. In ordinary materials banks made with a top width of about 10 ft. are usually strong enough to withstand the water pressure. Where a roadway is required on the bank, the top width should be not less than 12 ft. and preferably from 14 to 16 ft. In a climate where snow and ice prevail during a portion of the year roadways upon banks, except of considerable width, are dangerous and should be avoided for public travel.

Lateral Drainage.—In order to provide full protection for a canal, especially when located on sloping ground, it is necessary to provide for the care of lateral drainage. This feature, if neglected, may cause pools to form above the canal and, in periods of extreme rainfall, may result in an overtopping of the banks. The amount of lateral drainage which must be taken care of is a question somewhat difficult to determine. Especial study must be given to each particular case. The most satisfactory method of determining the amount of lateral drainage in a particular waterway is by past records of the quantity of flow. Information of this kind, however, is generally lacking, as flood conditions in ravines or small streams which are to be crossed by an irrigation canal are generally not observed. It is sometimes possible to determine from water marks the area of cross-section of a stream and from the general slopes of the country to form some estimate of the velocity and corresponding amount of discharge. Where such data are available they serve as a guide in determining the amount of drainage water which must be cared for.

Where all information relative to flow is lacking an estimate of the amount of runoff can be made from the catchment area, assuming a maximum rainfall per square mile. The amount of rainfall which must be assumed in this case will vary greatly in different parts of the country. The size of the drainage area is also a factor in determining the runoff per unit area, since, on small areas, the water is more quickly collected and approximates more closely to the total amount of rainfall on the area. For small areas, say, for example, from 1 to 5 square miles, the maximum runoff for a given period may reach approximately the total amount of water falling on the catchment area during the period. This, however, is exceptional. In providing for lateral drainage for the protection of canals it is necessary to consider extreme cases, and good practice demands that errors be on the side of safety in providing for a greater runoff than is necessary, rather than one which is too small for maximum conditions.

Lateral drainage may be cared for by diverting the water into the canal, or carrying it under or over the canal. The method which is most desirable in any particular case will depend upon local conditions. Where the quantity of lateral drainage is small and where it does not occur during the irrigation season it is frequently possible to carry it into the canal and dispose of it through some wasteway into natural channels. When lateral drainage must be provided for during the irrigation season this method is unsafe on account of the danger of exceeding the capacity of the canal. The method of diverting drainage into a canal is ordinarily by means of a flume or shallow channel down the upper slope of the canal.

Where the quantity of drainage is not excessively large, it may be diverted under the canal by means of a siphon or culvert. This method is particularly well adapted to locations where the canal is constructed in fill thus permitting a siphon or culvert to be constructed beneath the canal with a minimum amount of excavation. The upper bank in such a case also provides a small amount of storage which helps to control the drainage water. The filling up of the depression above the canal also raises the head on the culvert or siphon and increases its capacity during a flood.

Where large quantities of drainage water must be taken under a canal a common practice is to carry the canal in a flume supported by means of a suitable bridge or trestle work. In the location and design of a structure of this kind especial care should be taken to see that the opening below the structure is sufficiently large to provide for the maximum flow. A good example of a large canal being carried across a draw is the Spring canyon flume on the North Platte project, Nebraska. Here a canal of 1,400 second-feet capacity is carried over a canyon by means of a concrete flume supported by three reinforced concrete arches. The span of the largest arch is 50 ft. and the total distance spanned 110 ft. (See Plate VII, Fig. A.)

The third method of caring for lateral drainage, by taking it over a canal, may be accomplished by employing a flume or other structure for carrying the drainage water, or by carrying the canal beneath the natural drainage channel by means of an inverted siphon.

In general, where the quantity of lateral drainage is small, it may be taken care of by drainage into the canal or by a flume or culvert constructed either under or over the canal. Where the quantity large, however, or where the drainage area is considerable in amount, the better and safer plan is to allow the drainage to follow its natural waterway and to divert the canal either under or over the stream.

Right-of-way for Canals.—The cross-section and location of a canal having been fixed, the width of right-of-way required can be determined. On account of the ordinarily high values of irrigable lands it is desirable that no more be taken for right-of-way than is necessary, while, on the other hand, it is essential that sufficient width be procured to permit economical operation and maintenance. The width of right-of-way required depends, to a great extent, upon the size and importance of a canal. For main canals the right-of-way should be wide enough to include all embankments and in general with sufficient additional width to permit of work being done on these embankments without trespassing on adjacent property.

The right-of-way should provide, especially in the vicinity of embankments, a certain amount of space which can be used for borrow pits in case of emergency. The successful operation of a canal system or of a canal may depend upon having immediately available material for making repairs. Unless provision is made for this when the original right-of-way is acquired, there is no assurance in future years that needed material can be had at once. As lands are irrigated and the country becomes more thickly settled the value of land and the difficulties of acquiring additional right-of-way increase correspondingly.

The right-of-way for small and less important canals may be narrower than for larger canals. In every case, however, the right-of-way should be sufficient to provide for access along the canal for repairs and for needed materials for maintaining fills. For a small lateral, located practically all in cut and over comparatively level ground, the only right-of-way required in addition to the waterway is that necessary for travel along the canal. The same size canal located upon uneven ground or over a high fill would require a considerable amount of additional right-of-way in order to provide for material for repairing breaks in case of emergency.

There can be no fixed rule laid down as to the width of right-of-way which is required for any particular size canal. It must be kept in mind that for successful operation it is necessary to have unrestricted access to every portion of the canal system, and that for economical maintenance there is need of sufficient room for operation and of material for repairing breaks in case of an emergency.

Rights-of-way are of two classes: first, those which permit of the land being used for canal purposes, the fee or actual title thereof remaining with the original owner; and, second, ownership in fee simple. Ordinarily a title to a right-of-way which permits of the construction and operation of a canal only is objectionable, on account of certain rights which the original owner of the land may have thereto. For this reason it is believed that rights-of-way for main canals should be purchased outright so that the canal owners will be free to handle the construction and future operation and maintenance without restriction.

CHAPTER V

CANAL STRUCTURES

Classification.—Under the term "Canal Structures" are usually included all appurtenances outside of the main waterway of the canal together with any devices necessary for carrying the main waterway over or under streams, such, for example, as flumes, siphons, etc. In accordance with the purpose for which they are intended, canal structures may be classified under three heads, as follows:

1. Structures for diversion and controlling of water.
2. Structures for protection.
3. Miscellaneous structures.

Under the first classification, structures for diversion and controlling of water, are included head gates, which regulate the amount of water diverted into a canal; turnouts, for controlling and regulating the amount of water diverted from a canal, and checks and drops, which regulate the surface elevation of water in a canal.

Under the second classification, structures for protection, are included wasteways for discharging excess waters from a canal to prevent its being burdened above its normal capacity and also for emptying the canal in cases of emergency. There are included in this class also culverts and other structures intended to remove excess waters from the canal and prevent the banks being overtopped.

Under the head of miscellaneous structures are included bridges and like structures made necessary by the presence of the canal. Structures of the latter class may or may not have a part in the operation or maintenance of a canal and are not necessarily a part of the canal system. They are necessary, however, for the use of individuals or the public in general to compensate for the inconvenience caused by the construction of the canal and must therefore be considered as a part of the appurtenances of such canal.

Permanent and Temporary Structures.—Canal structures are sometimes also classified as temporary and permanent. A permanent structure is one, the location and duties of which are sufficiently well known, that can be built of lasting materials and in such a manner as to serve during the life of such materials. A temporary structure is one, the location or purpose of which has not been definitely determined or one which on account of future developments, will be rendered useless and can be removed at the end of a short period.

In the laying out and construction of distribution systems it is frequently advisable to provide temporary measures for delivering water on certain areas before final work is completed. In such cases the use of temporary structures is justifiable. It frequently happens also that changes in the methods of irrigation will be made, which, when effected, will require different modes or points of delivery. In such cases the use of temporary structures is also justifiable.

In the design and location of structures, especially those pertaining to the delivery of water, it must be remembered that irrigation is not yet developed to the point of an exact science and that specific cases will be encountered upon which we have little or no previous experience and where the choice between two different methods is difficult. In cases of this kind it is frequently justifiable to construct works of a temporary character to be utilized in a somewhat experimental manner until the proper data for location and construction of permanent works can be obtained. Except in such cases as above mentioned, which it is believed are generally rare, structures so far as consistent with cost should be made of as permanent a character as possible in order that they may afford ample protection to the system during the period of its operation.

Headgates.—The function of a headgate is to control and regulate the discharge of water into canals. The term "headgate" is generally applied to the larger structures, such, for example, as those at the head of main canals or laterals. The requirements for headgates for a canal are as follows: First, they shall be strong enough to withstand the maximum pressure and head of water which is imposed upon them; second, they shall have sufficient capacity to divert the maximum flow of the canal; third, they shall permit of regulation sufficient to control with accuracy the quantity of water being diverted.

In the design of a headgate first consideration should be given to the question of its stability. On a large or important canal the headgates serve as a protection for the canal system and property thereunder. On account of this important function no pains should be spared in the design and location of such structures to make them absolutely safe, and of as permanent a character as is consistent with reasonable expenditure. Permanent headworks on important canals are usually constructed of masonry, the ordinary type of design being some form of gravity structure amply heavy to

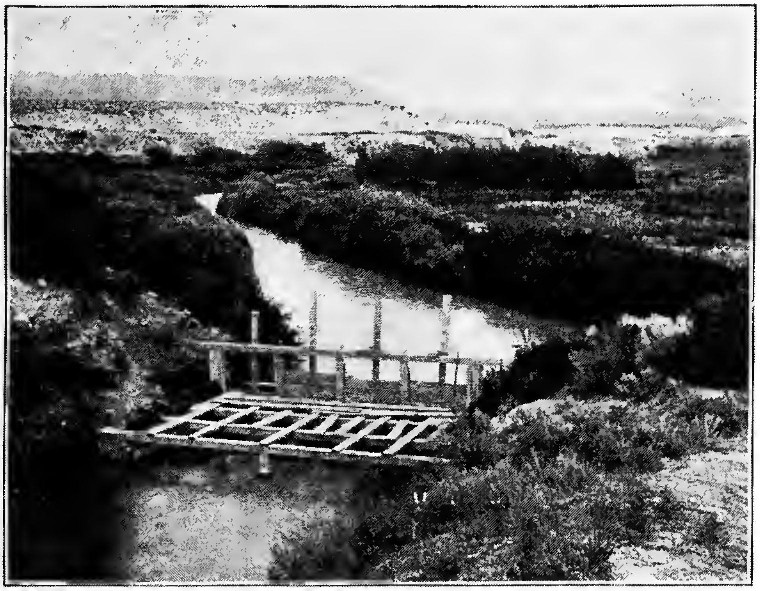


FIG. A.—Wooden headgates, typical of those usually built for the earlier canals. Jordan and Salt Lake City Canal, Utah.

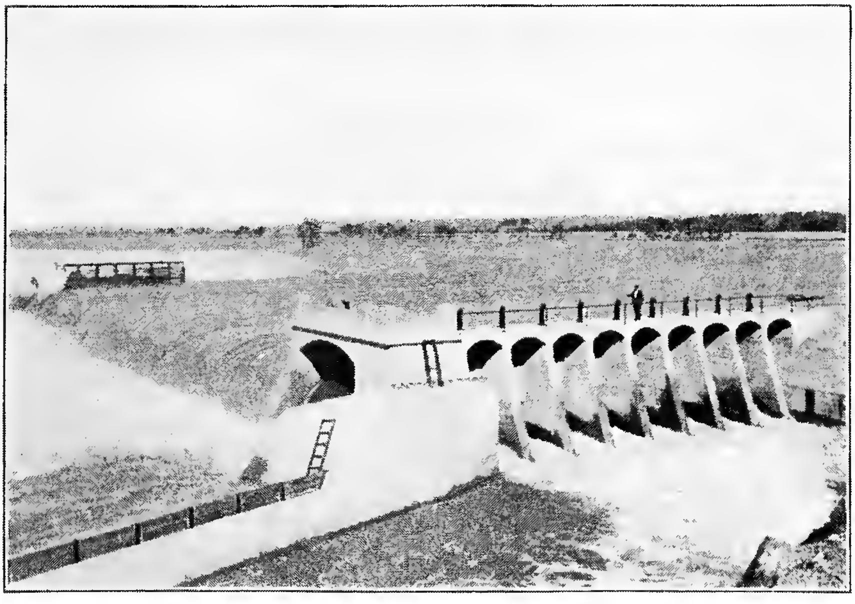


FIG. B.—Concrete headworks with steel gates. Interstate canal, North Platte Project, Nebr.

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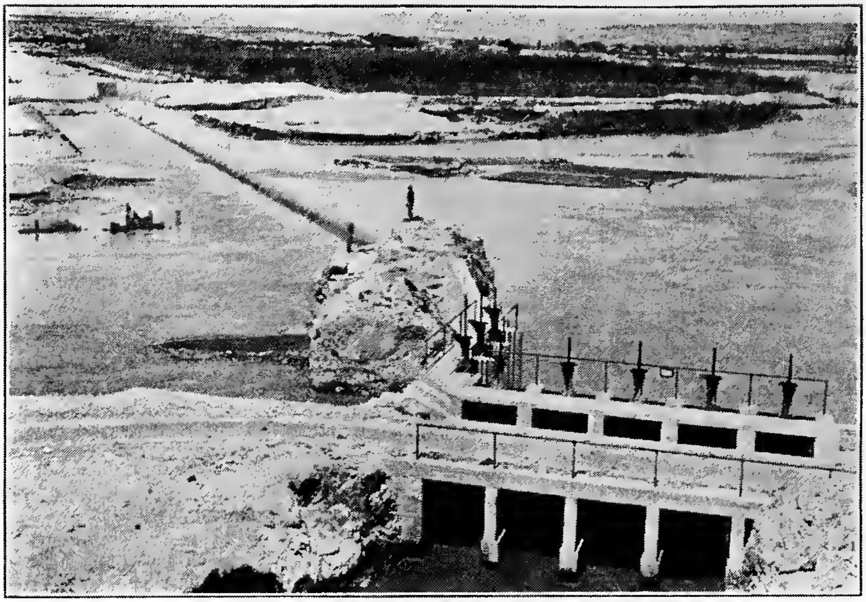


FIG. C.—Concrete headworks and roadway, Mesilla Valley canal. Rio Grande Project, N. Mex.

FIG. D.—Concrete headworks with sluice gates at Laguna dam on Colorado River, Ariz.-Cal.

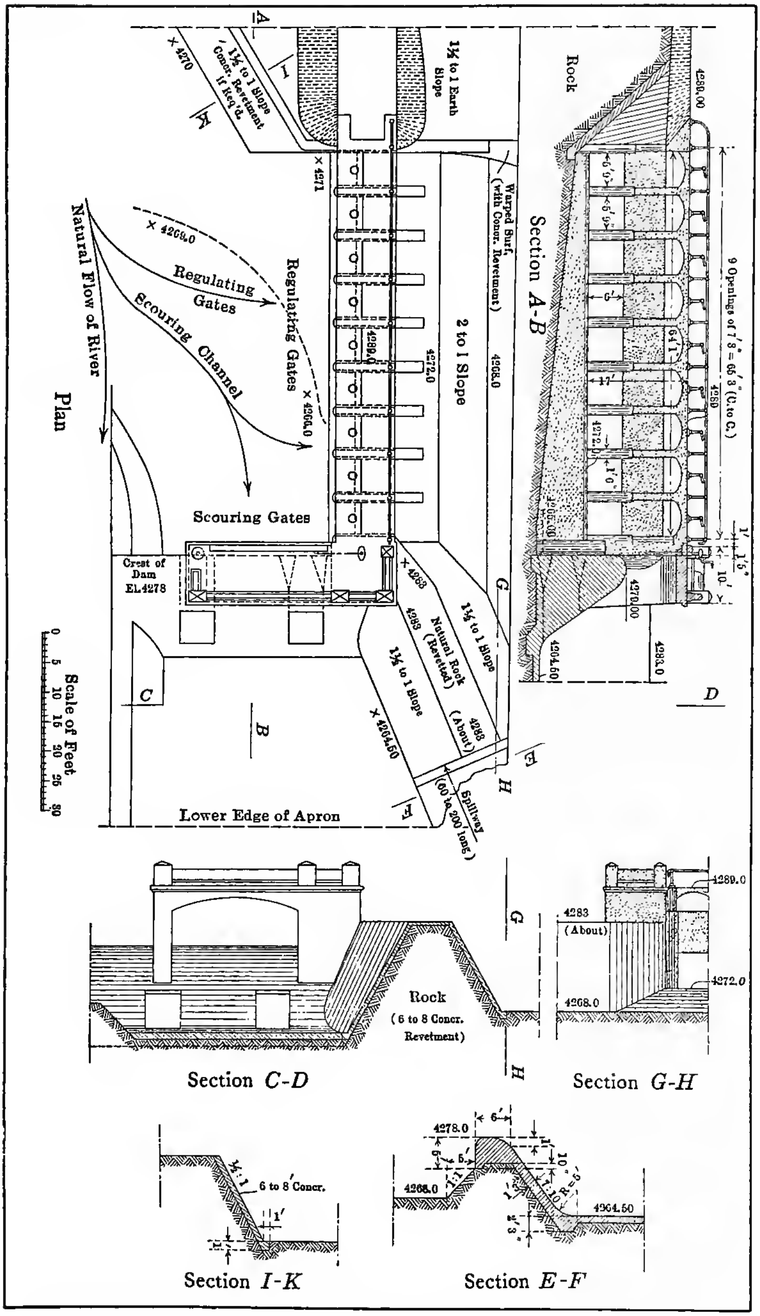


FIG. 14.—Head-works for Interstate Canal, North Platte Project, Wyoming-Nebraska.

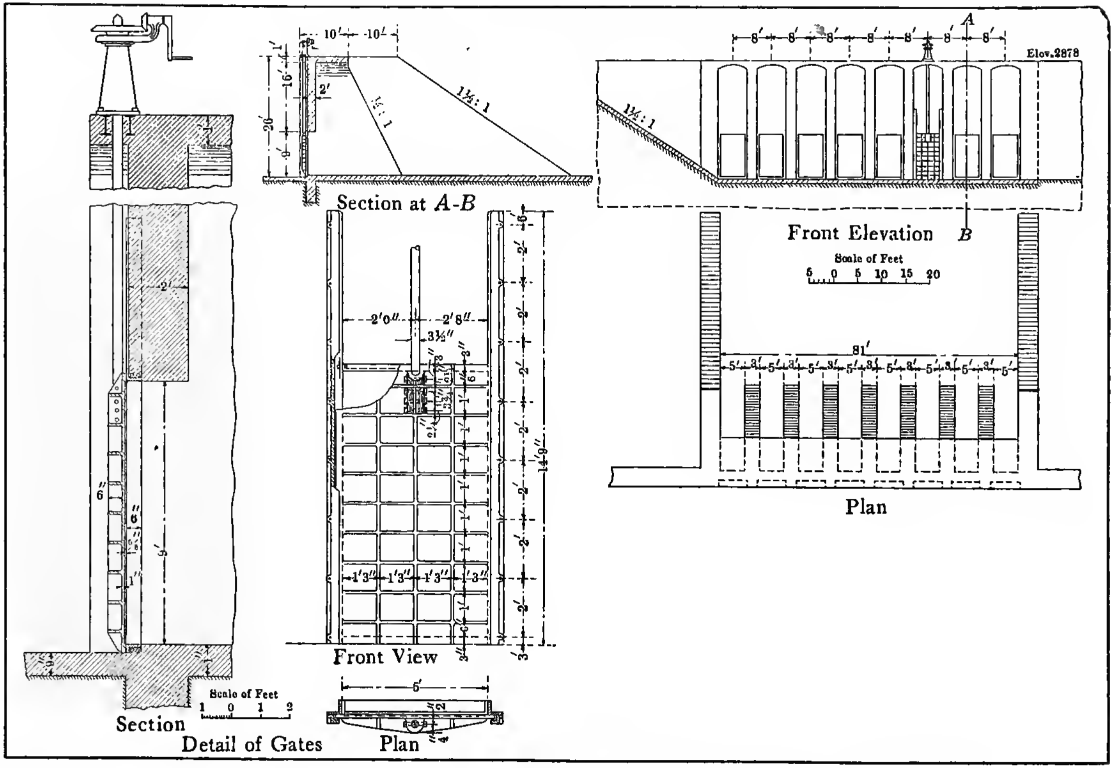


FIG. 15.—Canal headworks and gates, Boise Project, Idaho. (See also Plate I, Fig. A.)

resist overturning with the maximum head which may be imposed upon it.

Another important factor in the design and construction of headworks is to provide sufficient curtain and wing walls to prevent seepage either under or around the structure. The extent of such protection against seepage will depend upon the amount of head and the character of material in which the structure is placed and no general rules can be laid down for designs of this kind. It is, however, essential that a complete study and investigation be made in each particular case.

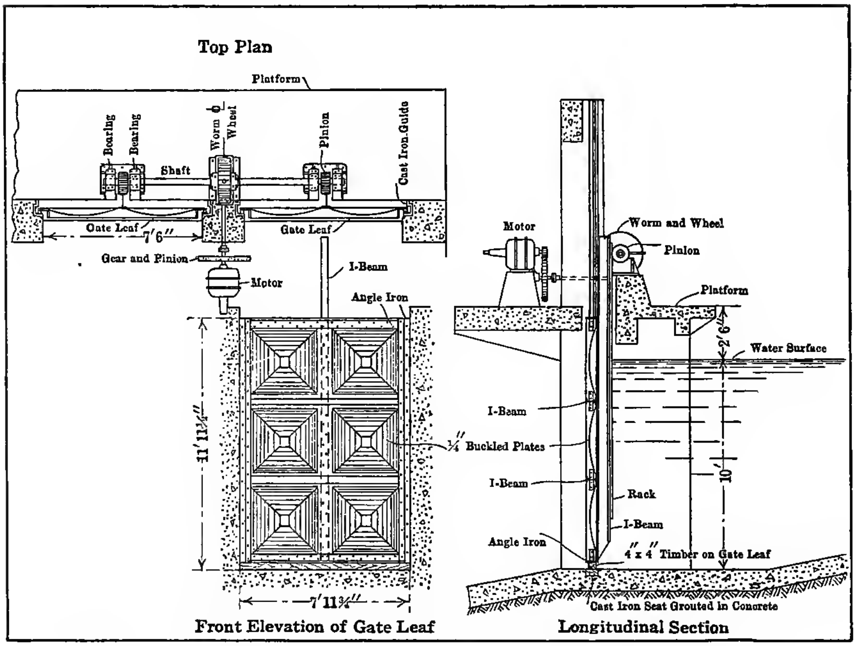
In backfilling around headgates the greatest care should be given both to the character and manner of compacting the material. Under ordinary conditions the greatest degree of compactness can be obtained by the use of water, that is, by either wetting the material to a slight degree and tamping it or by depositing it in water.

The capacity of a headgate should be computed not only for the maximum capacity of the canal but for various stages of water both above and below the headgates. It is frequently necessary, especially where a water supply is limited, to operate a canal at part capacity. Where this is necessary a headgate should be so designed that the full capacity of the canal up to any level can be drawn from the source of supply without undue loss of head at the structure. In determining these functions it is necessary to consider both velocity and entry head and the entry coefficient. These principles apply especially where diversions are made from fluctuating heads as, for example, from streams without ample diversion weirs.

Operating Device.—The essential characteristics of the operating device are that it be simple in operation and capable of controlling accurately the amount of the discharge. Various forms of controlling devices are in use. They vary from the simple flash boards which may be operated by hand to carefully designed and constructed metal gates operated by means of electric or other power. On account of the difficulty of operation, the flash-board control is not recommended for important diversion points.

The type of controlling apparatus which appears most satisfactory for main canals and which is rapidly replacing the older type of flash board or wooden gates recently built in irrigation systems is some form of metal gate operated by a screw driven by hand or machine power as shown in Fig. 15. The advantages of a device of this kind are that it is susceptible of a slight motion and furnishes the means for regulation to any desired quantity. Whether or not power is necessary depends upon the amount of energy necessary to be expended and the time required for opening or closing the gates.

A satisfactory conclusion on this point can be made only by careful computations. To take a concrete example, we will consider a gate 5 ft. square, subjected to a maximum head of 20 ft. at its central point. The total pressure on the gate will be $p = 62.5 \times 25 \times 20 = 31{,}250$ lb. Assuming the coefficient of friction between the gate and guides to be 0.25, the total force, exclusive of the weight of the gate and stem, required to start it from a position of rest will be $0.25 \times 31{,}250 = 7{,}812.5$ lb. To raise this gate at the rate of 1 ft. per minute, if we assume the weight of the gate to be say 3,000 lb., will require the expenditure of 10,800 ft.-lb. of energy per minute or approximately 1/3 h.p.


Top Plan

Front Elevation of Gate Leaf

Longitudinal Section

FIG. 16.—Electrically operated sluice gates, Salt River Project, Arizona.

In some cases, where the water supply carries large quantities of silt in suspension which it is desirable to prevent entering the canals, special forms of headgates or diversion works are used. The most common method of preventing silt from entering the canals is by skimming the water from the surface thus leaving the heavy silts which are carried nearer the bottom undisturbed. To accomplish this, flash boards, the top portion of which can be removed, or gates which can be lowered so as to allow the water to pass over them, are used. Where this form of diversion is employed it is necessary to construct sluice gates for removing the silts which are deposited above the headgates. These sluice gates, in order to be effective, should be placed near the diversion gates and should also be at a considerably lower elevation.

The diversion works at the Laguna Dam near Yuma, Arizona, shown on Plate V, Fig. D, consist of a series of overflow gates of sufficient width that the supply is drawn from the upper 4 ft. of the pool above the dam. The accumulated silts are removed by means of sluiceways, the bottoms of which are approximately 13 ft. below the top of the dam. These sluiceways are controlled by means of electrically operated gates each having a clear opening of 33 ft. 4 in. wide.

Turnouts.—Under the term "turnout" are included structures for diverting water from the main canals and laterals to the distributaries and farm ditches. The most common form of turnout, and one which seems most satisfactory, consists of a box or pipe opening through the bank of the main canal and controlled on the inner side by a gate or flash board. To provide for drawing a supply from the canal when it is only partly filled, turnouts should be located as low as possible. On account of the important position they occupy, and the difficulties of renewing them, turnouts from main canals should be of permanent construction. Where the amount of water to be diverted is considerable, a solid conduit of masonry or concrete should be used as shown in Fig. 17; where only a small opening is required vitrified or cement pipes laid with tightly cemented joints are satisfactory as shown in Fig. 18.

In the placing of the turnout, cut-off walls should be constructed around the conduit or pipe and the earth filling around them should be carefully tamped or puddled in order to prevent seepage and a possible washing out of the structure. Where very large openings are required, as, for example, at the diversion to a large lateral, masonry or concrete sluices, controlled by gates, are constructed through the banks. The upper and lower ends of turnouts should be protected by means of ample wing walls or heavy water-tight paving on the slopes to prevent erosion and seepage. Each turnout should be provided with a means of controlling the flow, so arranged that it can be easily operated, and securely fastened in position.

On the older canals most of the turnouts as well as other structures were built originally of wood. A drawing of the details of one of the ordinary wooden boxes is shown in Fig. 19.

Where the head on a turnout is considerable, say above 3 ft., it

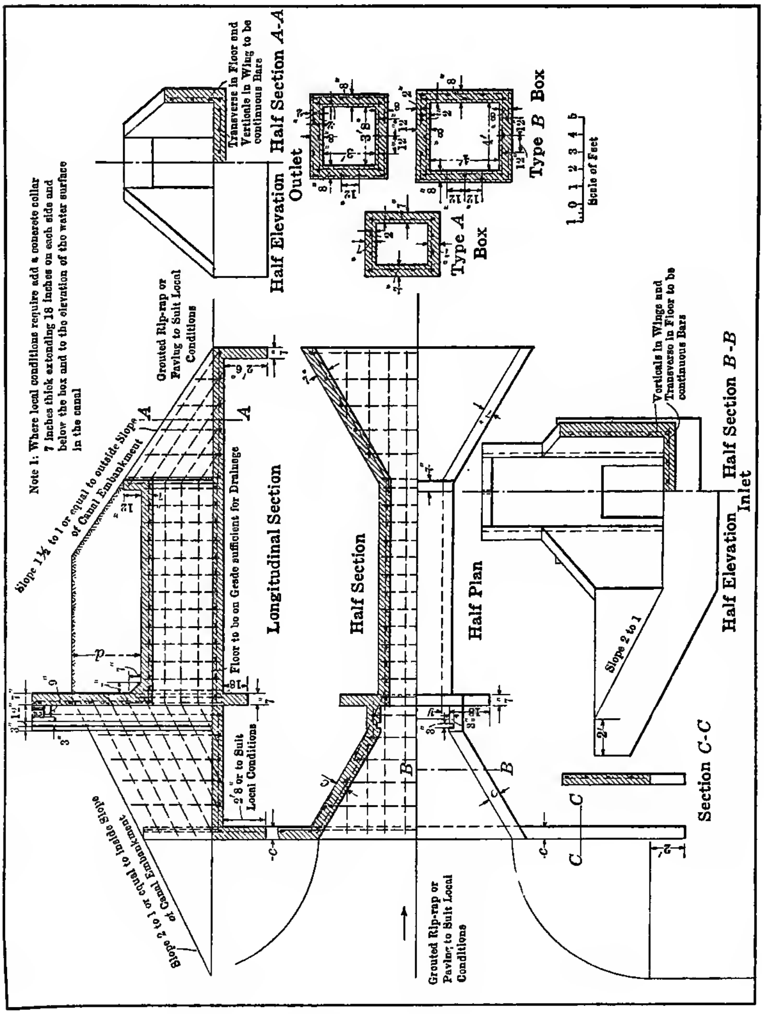


FIG. 17.—Reenforced concrete turnout.

should in general be controlled by means of gates. For low heads, flash boards may be used. They are, however, more or less unsatisfactory in important structures on account of the difficulty of regulating the flow and the tendency to constant leakage.

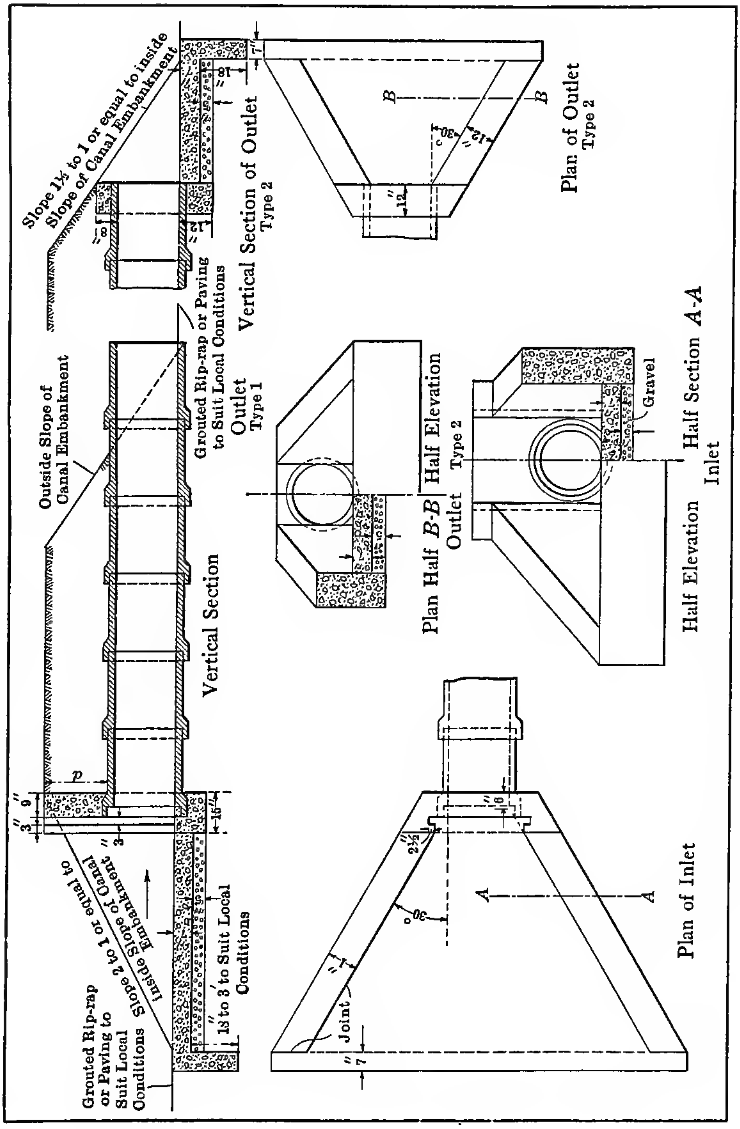


FIG. 18.—Turnout of vitrified pipe with concrete inlet and outlet.

The capacity of a turnout will depend upon the capacity of the canal which it serves. It should be designed to furnish the required amount of water with the minimum head in the main canal at which

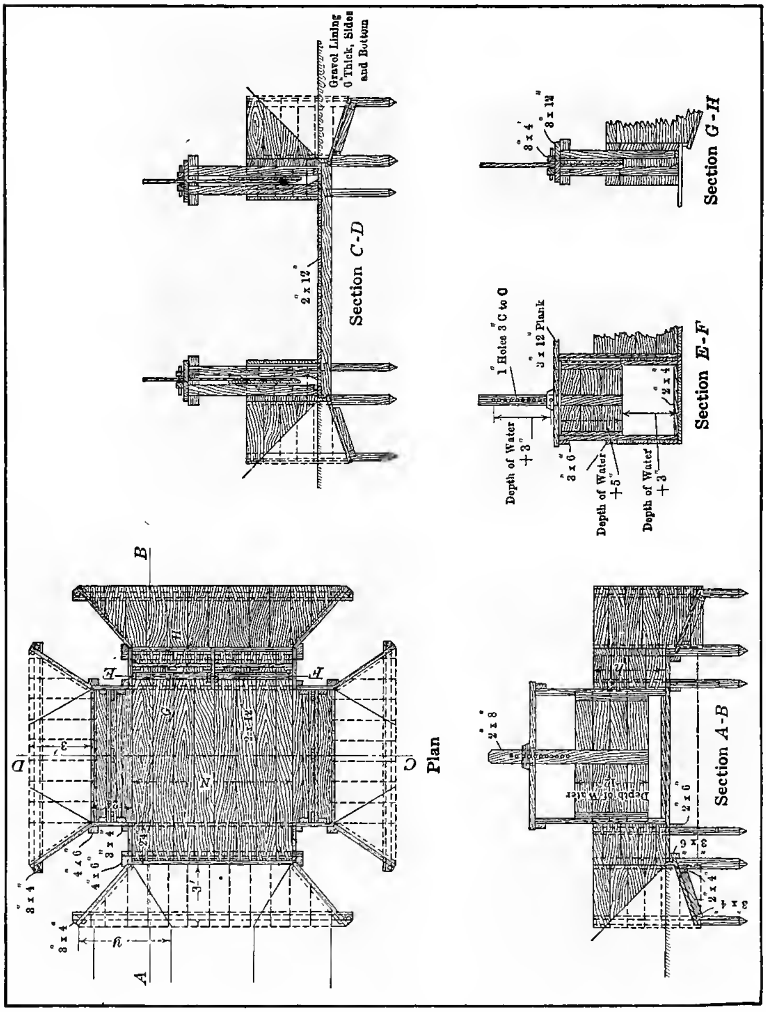


FIG. 19.—Typical wood division box for small laterals of older canals.

it is to be operated. When the pipe or conduit is short, so that its friction may be neglected, the velocity of flow through it may be computed from the formula $V = C\sqrt{2gh}$. Where h equals the head in feet, g the force of gravity and C a constant depending upon the shape of the orifice, but having an average value of about 0.8.

Checks and Drops.—Checks and drops are used to regulate the surface elevation and velocity of flow in canals.

The term "check" is commonly applied to a structure which closes a part of the waterway of a canal and holds the water on its upstream side at a greater elevation than on its downstream side. Checks are sometimes built in the form of long-crested overflow weirs extending across the canal and sometimes in the form of a structure carried well up above the water surface and having an opening or openings through which the water discharges. In each of these forms there is a drop in the water surface in passing it. The chief purpose of a check in a canal is to hold up the water surface at delivery points while the canal is being operated at part capacity. This permits water being delivered to lands which, in some cases, could not otherwise be reached except with the canal running full. Checks are also sometimes used to reduce grades and thereby lessen the velocities in canals.

The term "drop" is applied to a structure through which water is transferred from a higher to a lower elevation. Drops are used where the slope of the country over which a canal passes is greater than the allowable slope of the canal, the real purpose of the drops being to reduce the effective grade or slope in the canal, and thereby lessen its velocity by using up a portion of the grade in vertical or nearly vertical falls.

The accompanying Fig. 22 gives the principal dimensions of the ordinary drop built of timber such as has been employed on the older canals. On the larger systems now being built throughout the West these are replaced by concrete structures such as is illustrated in Fig. 23.

Drops are commonly of two general types, classed as vertical or inclined. In a vertical drop the water is allowed to fall freely, while in an inclined drop it is carried down an incline by means of a chute or some form of channel built of material not easily eroded. Water in passing a drop acquires velocity which must be destroyed before it enters the channel below, in order to prevent erosion. The most common method of destroying this velocity is to allow the moving stream to fall into a pool of water at the foot of the drop. The pool in this case forms a water cushion which absorbs the energy of the falling water. Water cushions may receive the stream either vertical or at an angle inclined to the vertical. In the latter case the impingement of the stream into the water below causes currents

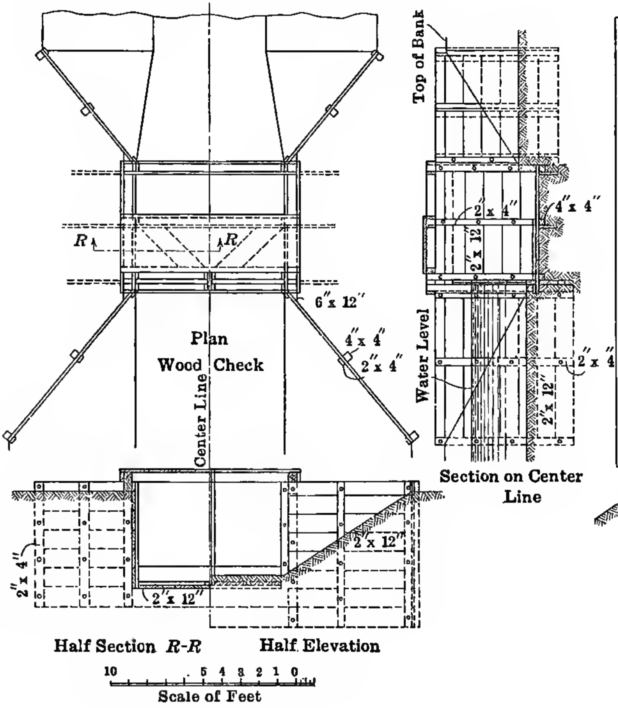


FIG. 20.—Wooden check with flashboard control.

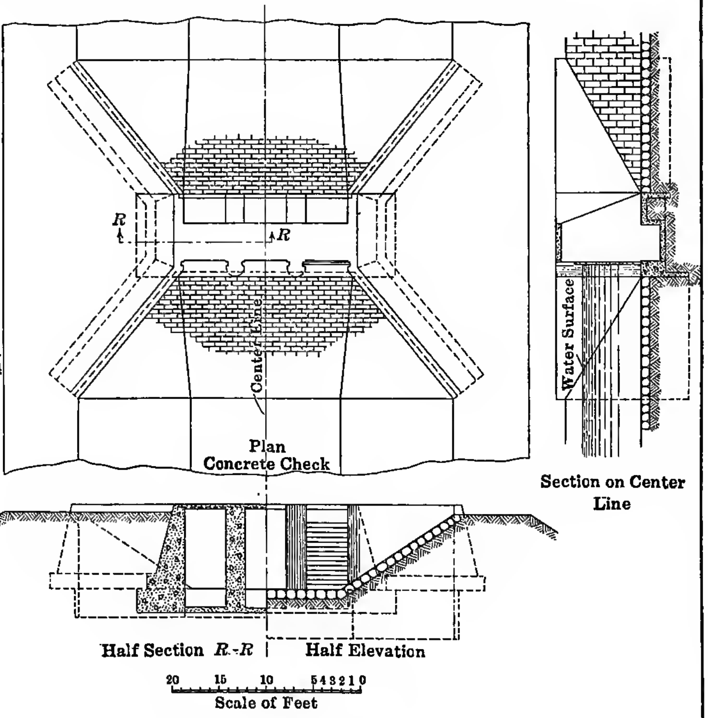


FIG. 21.—Concrete check with flashboard control.

which tend to serious erosion in the sides of the channel near the foot of the structure. (See Plate VI, Figs. A and B.)

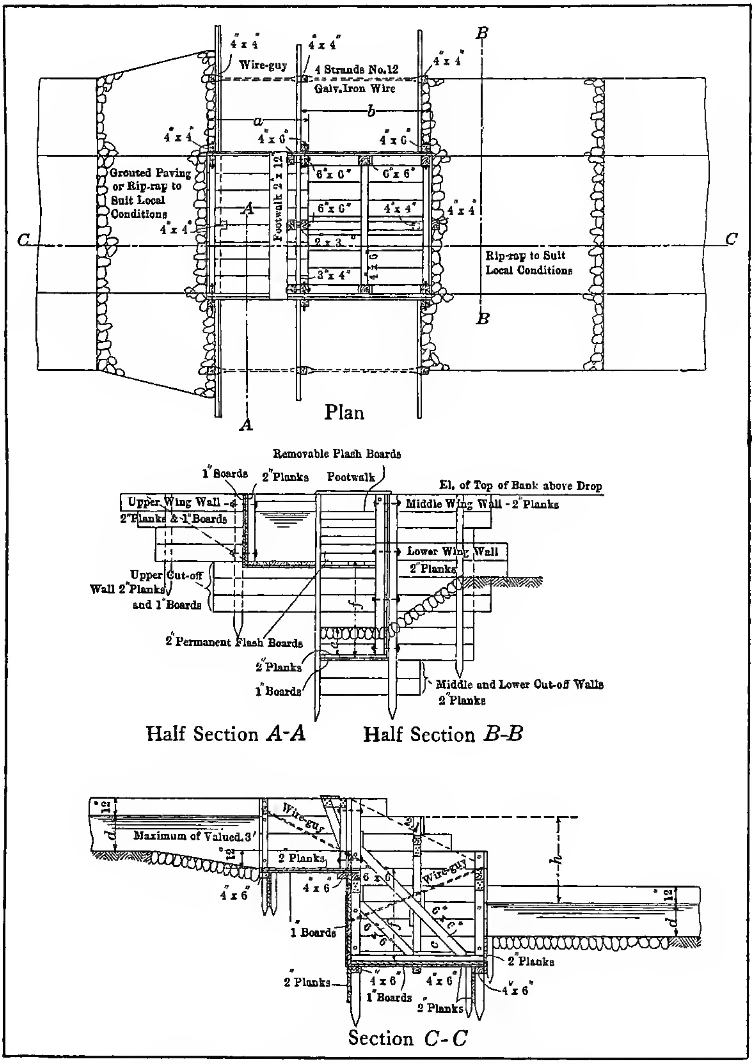


FIG. 22.—Type of timber drop for small canals.

In vertical drops there is a less tendency to erosion in the sides of the channel. Since, on account of the absence of the horizontal component in the velocity, fewer currents are set up. There is a tendency, however, in vertical drops for erosion to take place in the bottom of the channel, where the stream impinges. The remedy against erosion in either case is to provide sufficient width and depth of water cushion to receive and absorb the shock of the falling water without allowing it to impinge on the walls or bottom of the cushion with sufficient force to injure them. Where a water cushion is to receive any considerable velocity it should be built of masonry or other permanent material.

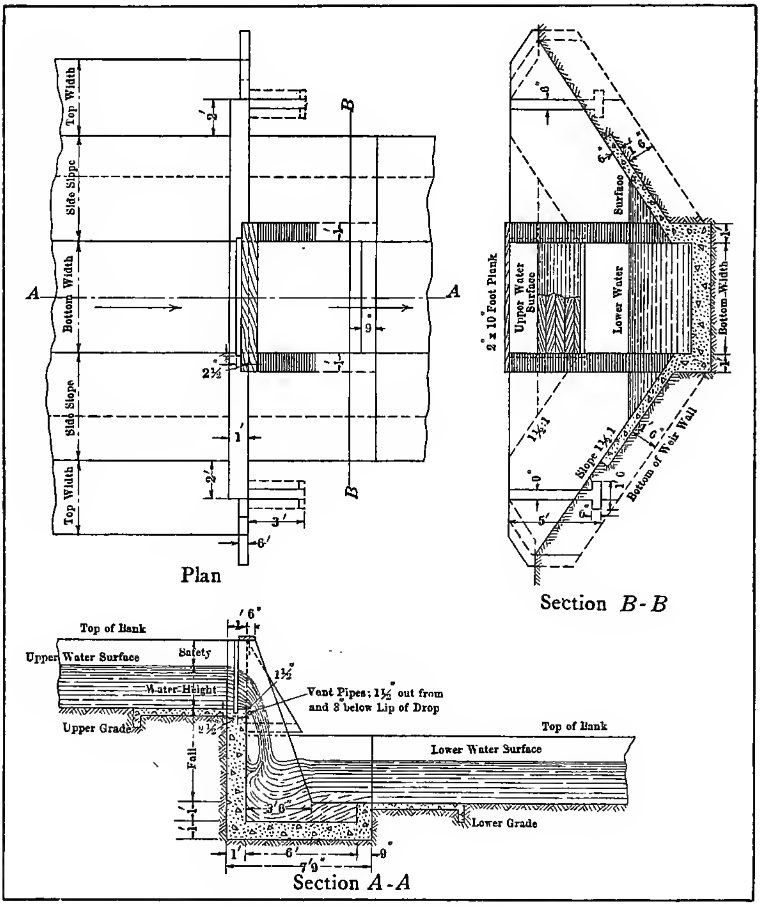


FIG. 23.—Type of concrete drop.

The size and depth of water cushion required for a given head and quantity of flow are questions upon which engineers are somewhat at variance, and experimental data for determining the proper relations of these quantities is lacking. Some observations made in India show that where the ratio of height of fall to depth of water cushion is as 3 to 4, the flow had no injurious effects on the bottom of the pool. So far as known, however, no careful set of observations showing the relations between height of fall, quantity of discharge and depth to which the effect of the stream is appreciable, have ever been made.

In practice, water cushions are usually constructed with a depth of about one-third that of the maximum fall, that is, one-third of the height of weir above the surface of water below it, plus the maximum depth of water flowing over the weir. It is believed that for drops where the height of fall is not great this depth of cushion is sufficient. The length of cushion required will depend somewhat upon the height of fall and quantity of water discharged. It should be sufficient to permit the water to come to a nearly quiescent state before it reaches the ordinary section of the canal below. The minimum length of cushion should not be less than three or four times its depth. The width of a cushion should be somewhat greater than the length of the overflow weir. One of these inclined drops or reinforced concrete chute designed to take the place of ordinary drop on a steep grade is shown in Fig. 24 with water cushion at the bottom.

With inclined drops of considerable height, a type of channel is sometimes used which offers a large amount of resistance to the flow of the water and prevents it acquiring a high velocity in its descent. These channels are sometimes constructed of rough stones so placed as to offer the maximum resistance to flow. In addition to the rough walls and bottom, rock barriers projecting above the water surface are placed at frequent intervals in the channel. Another and very effective method of reducing velocity in an inclined drop is to construct it in the form of a series of vertical drops with a water cushion at the foot of each. By such a device the velocity is killed at each water cushion and the maximum velocity which will be acquired will depend upon the height of the secondary drops.

In the design and construction of drops for a canal over country where the slope is considerable, it is necessary to do a large amount of preliminary work in order to reach the most economical solution. The principal points to be considered in this connection are the

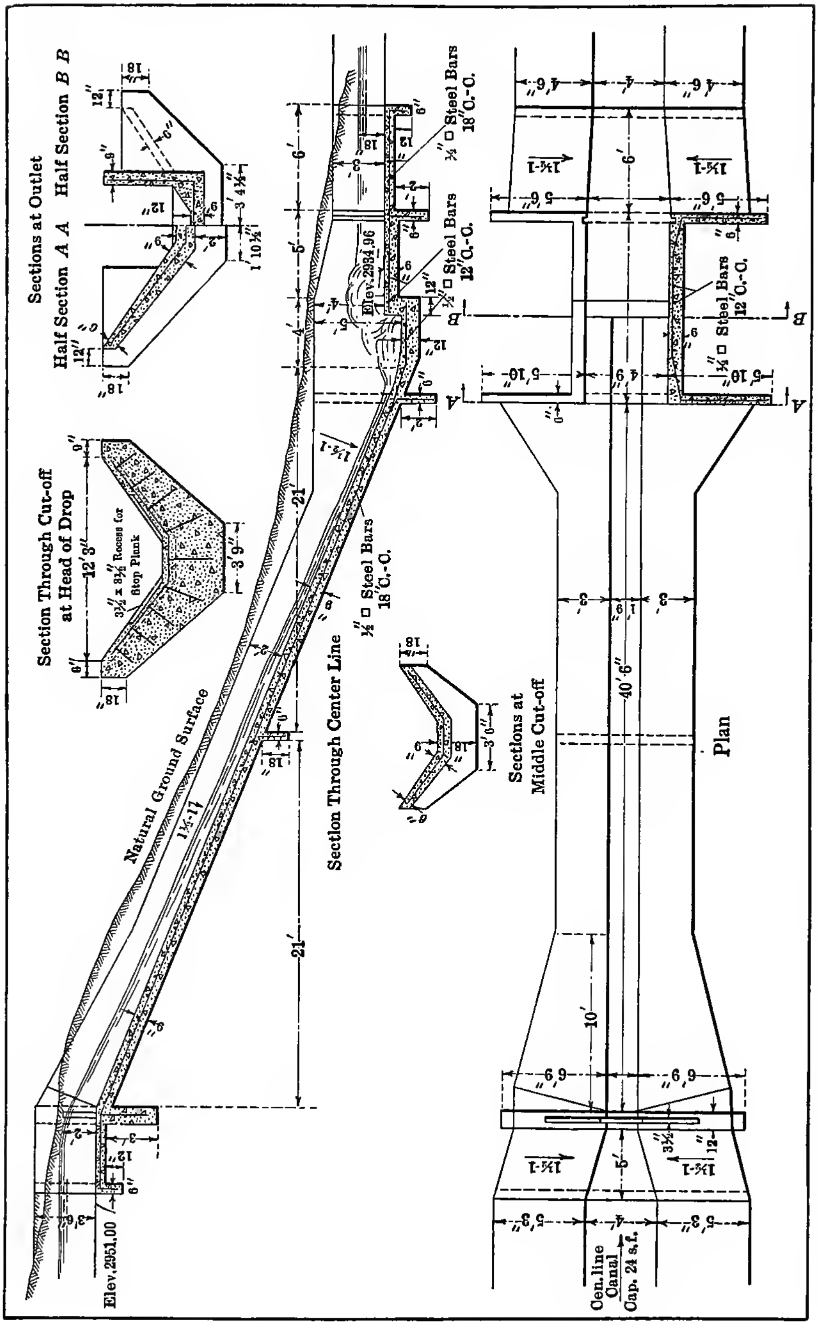


FIG. 24.—Reenforced concrete chute, designed to take the place of a vertical drop down a steep grade, Huntley Project, Montana.

relative costs of a canal with fewer drops of greater height, compared to one with more drops of lesser height. In the former case it must be taken into account also that more excavation will be required on account of the increased depth of the canal below the high drops. In some cases where the slope of the country is very great it is more economical to line a canal with masonry so that it will stand high velocities, than to construct the necessary drops to reduce its velocity to a maximum for an earth canal. The latter method is in effect the construction of a long inclined drop. No general statements can be made relative to the most economic method of handling special cases, each must be considered in the light of all factors which affect its efficiency and cost in order to reach a satisfactory solution. (See Plate VI, Fig. C.)

Checks and drops are frequently combined in one structure, which is, in fact, simply providing a means for holding up the water in the canal above the drop. This may be done by a flash board or gate regulation, the size of opening being adjusted to hold the water up to the required height. The up-stream side of a drop is sometimes constructed as a weir with its crest raised some distance above the grade of the canal. This weir automatically acts as a check for holding the water up in the canal but has the disadvantages of increasing the height of drop for low discharges and not permitting the canal to drain completely. All drops of this kind should have a small drain to completely unwater the canal. Immediately above a drop which is given a free discharge there is a rapid drawing down of the water in the canal and a corresponding increase in the velocity of the flow. These high velocities have a tendency to destroy the canal above a drop and if for no other reason than that of protection it is ordinarily necessary to regulate the flow over a drop so that the water above will not be drawn down to any appreciable extent. One method of doing this is by means of the notched drop.

This notched drop (Fig. 25) is used extensively in India and has been introduced in the United States. In this form of drop the canal discharges from the upper channel into the pool below through one or more notches of such size and shape that the amount of flow through them for any given depth is very nearly equal in amount to that carried by the canal with the same depth. A notch which for all depths will theoretically discharge the same quantity of water as will be carried by a trapezoidal canal section has curved sides and bottom. Practically, however, this refinement is unnecessary, and a notch may be made with straight sides and bottom

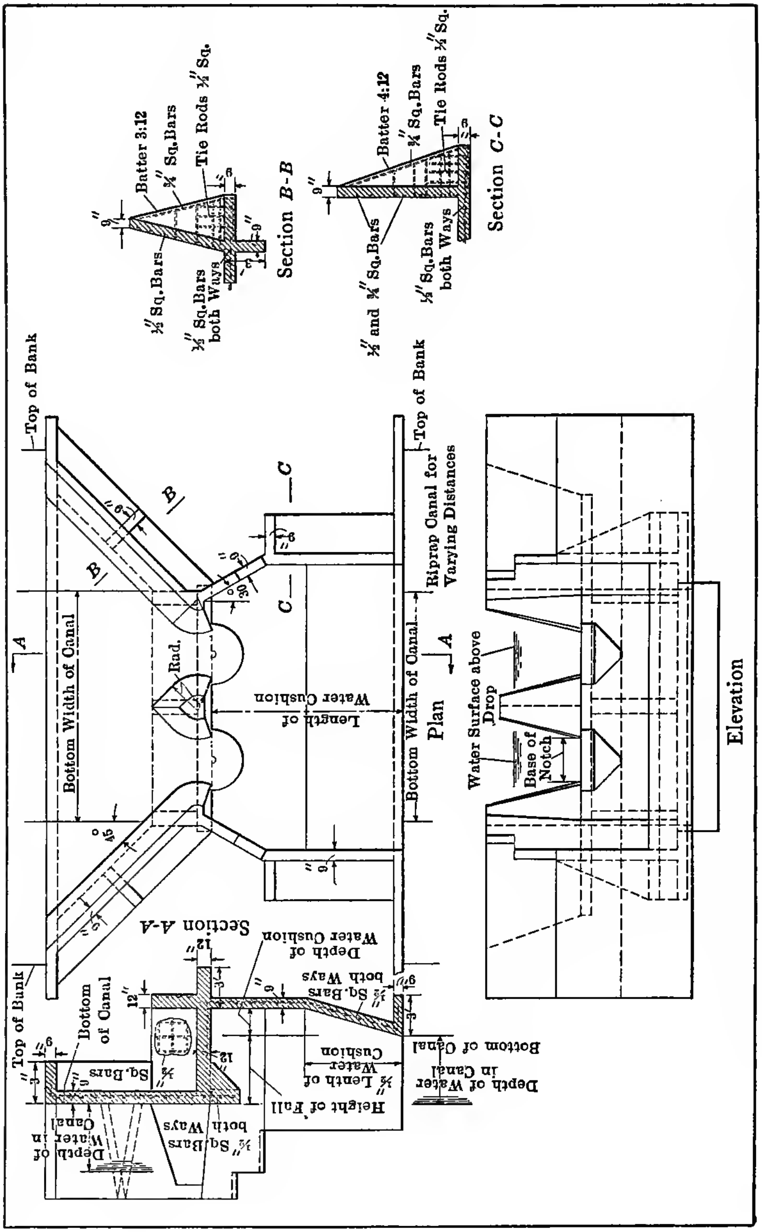


FIG. 25.—Notched type, reinforced concrete drop, North Platte Project, Nebraska.

which will fulfill practical requirements. The exact shape and size of notch, that is the width of bottom and slope of the sides, which is required, will depend upon the size and section of the canal and must be designed for each particular case. With drops of any considerable size it is preferable to use several notches instead of one. This permits the water being broken up and distributed more nearly over the entire surface of the cushion below and reduces its cutting effect. If a semi-circular lip be projected for a short distance down-stream from the foot of each notch the water can be further spread out and its erosive effect still further diminished. (See Plate VI, Fig. B.)

Wasteways.—The term "wasteway" applied to canals, includes two distinct classes of structures. The first, which is commonly called an overflow spillway, is used to discharge the waters from a canal when it becomes filled above its normal capacity. Such a spillway is automatic in its action and serves as a safety valve to prevent a canal being overloaded and its banks topped and washed away. The second class of structures commonly known as a sluice gate, is used for emptying a canal. Sluice gates in general are not automatic in their action, but are ordinarily provided with the necessary means for opening them quickly. They serve as a means for rapidly drawing down the water in a canal in case of an emergency, such as a break, or when repairs are necessary.

Overflow spillways and sluice gates are both to a large degree protective in their nature; the first providing a safeguard against accident, and the second a means for reducing the damage should an accident occur. It cannot be said that the use of either is absolutely necessary at a particular place in a canal, but experience has shown that the protection which they afford to an important canal is well worth their cost.

The requirements for location for the two classes of structures do not differ greatly. In one important respect, that of requiring a wasteway channel, they are similar. In other words, in the location of either a spillway or sluice gate a site must be selected from which it is possible to carry the waste water without undue damage to the adjacent lands. On this account it is sometimes feasible and economical to construct both a spillway and sluice gates at the same point on a canal. The location of these structures should be such that they are accessible and provide for the greatest degree of efficiency. In general they should be located at or near the lower end of that stretch of the canal they are intended to protect, since at this point the protection from overflow and the drainage of a canal can be most easily effected. The frequency at which the structures should be located is dependent upon the size and importance of the canal.

In the design of an overflow spillway there must be considered first the maximum quantity of water it shall discharge, and second, the maximum rise above the normal elevation of water surface which the canal will stand. These factors are both uncertain and may in some cases be classed as mere assumptions. In general it may be assumed, however, that the maximum capacity of an overflow spillway need not exceed 50 per cent. of the capacity of a canal, and that the maximum rise of water in the canal should not exceed from 30 to 50 per cent. of the minimum free board.

Having established the discharge and head of water available, the length of spillway required may be computed from the weir formulæ by selecting the proper coefficient for the particular form of weir crest to be used. The form of weir crest and channel to be used will depend to a great extent upon the topography of the site and the character of the material. Spillways should as a rule be located where the canal is well in cut in order to provide safe foundation for the overflow weir and waterway leading from the weir over the banks. This waterway should be water tight and for safety should be of permanent masonry construction.

For collecting the discharge from a long weir and concentrating it in a channel of small width various methods have been used. One is to construct the upper portion of the outlet channel parallel to the weir crest and discharge into it laterally. Another method is to concentrate the length of overflow weir by constructing it in a dentated form, thus reducing the total width of spillway opening.

A sluiceway for the protection of a canal should in general have a capacity not less than that of the canal so that if necessary the entire flow may be diverted. The bottom of a sluice gate should be some distance below the grade of a canal, in order to increase its capacity and make it more effective in its operation. The gates closing a sluiceway should be of a type easily operated and fitted with the necessary devices to insure their operation when required.

Culverts.—In connection with canal construction, culverts are used: first to carry drainage water under the canals, and, second, to carry canals under roadways or through embankments where open cuts are not feasible. Whether a culvert be used for carrying water

FIG. A.—Series of checks and drops with inclined chutes terminating in water cushion with concrete blocks to break the force of the water. North Platte Project, Nebr.

FIG. B.—Notched check and drop with projecting lip beneath each notch to diffuse and break the force of the falling water. Rio Grande Project, N. Mex.

PLATE VI

FIG. C.—Concrete chute, built instead of a series of drops, and terminating in a water cushion with concrete baffle board. Boise Project, Idaho.

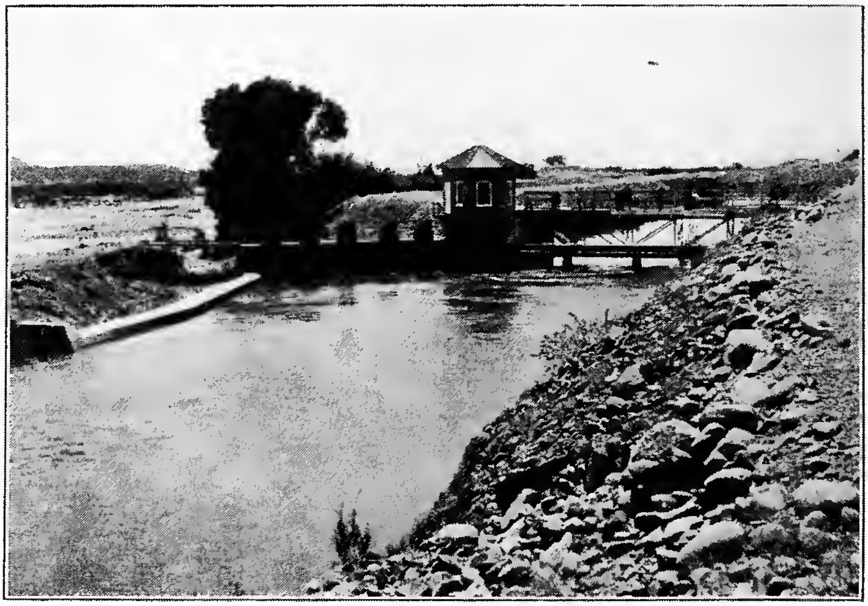


FIG. D.—Spillway lip to automatically permit escape of excess water from canal back into river and sluice gates provided to facilitate scouring out of materials deposited in upper portion of canal. Salt River Project, Ariz.

under a canal or whether it be used for carrying the waters of the canal, the general principles of its construction do not differ materially. The principal points to be considered in the design and construction of culverts are size or capacity, section, grades, economy and permanency of construction.

The capacity of a culvert to carry the waters of a canal will be limited to the capacity of the canal. The capacity of a culvert to carry drainage water under a canal was treated under Lateral Drainage. In this connection, attention is called to the fact that errors in the capacity of drainage culverts are likely to be on the side of making them too small rather than too large. It is impossible to prove that a culvert is too large but a very simple matter to prove that it is too small should its capacity once be overtaxed. The section of a culvert carrying an irrigation canal is important on account of the grade it may require. In order that no extra grade be consumed by the passage of water through a culvert its cross-section, both as regards shape and area, must be practically the same as that of the canal. If the area of the waterway be contracted so that a higher velocity is required in the culvert than in the canal, additional grade is necessary to produce and maintain the added velocity. If the shape of the waterway is changed additional friction results, which also requires head to overcome.

On account of the excessive cost, it is not practical in most cases, to construct culverts of the same shape and area of cross-section as the canal of which they form a part. In most cases, economy can be effected both by reducing the area of the cross-section and by building it of such a shape that the minimum amount of material is required for the maximum cross-sectional area. The most economic section, so far as hydraulic properties and amount of material required are concerned, is the circle. This section is not always practical, however, on account of the abrupt changes which it introduces in the channel. For example, a canal 2.5. ft. deep and having an average width of 20 ft. will have practically the same cross-sectional area as a circular culvert whose diameter is 7.3 ft. On account of the necessity of contracting the stream and the lowering of the grade of the culvert far below that of the canal a round culvert is not the most favorable for wide and shallow canals.

Where a culvert is intended to carry drainage water different conditions ordinarily prevail, and the same necessity for conforming the shape of the culvert to the shape of the canal does not exist. In general, however, the grade of a culvert should not be much below the grade of the waterway in order to avoid its being silted partly full and rendered less effective when it is needed.

The forms of culverts most generally in use are what are commonly designated as "barrel" and "box" culverts, the former being ordinarily a circle or ellipse and the latter of rectangular form. According to the materials used, culverts may be classified as wood, pipe, and masonry. Wood culverts are commonly constructed in rectangular form and consist of a framework sufficiently strong to carry the embankment above, covered with planking which forms the waterway.

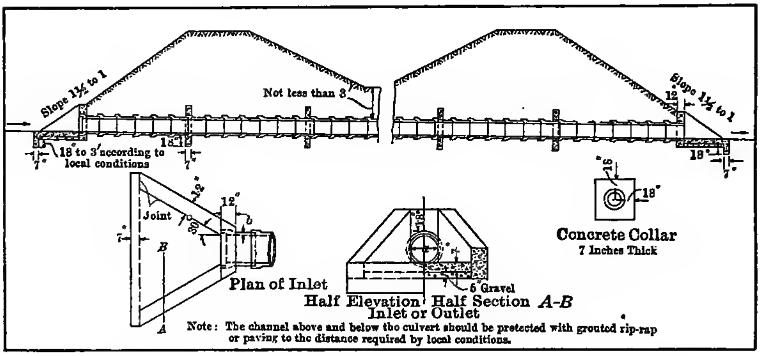


FIG. 26.—Vitrified pipe culvert with concrete inlet and outlet.

Pipe culverts (Fig. 26) are either vitrified, concrete, iron or steel. Masonry culverts are generally constructed of either stone or concrete.

The selection of the materials from which a culvert is to be made involves questions of cost, importance, and durability of the structure. In most sections of the country culverts can be constructed of wood at a less cost than from other materials. On account of the perishable nature of wood, however, it is not satisfactory for permanent work. For small openings, not exceeding say 4 or 5 ft. in diameter, pipe culverts are satisfactory. Whether or not vitrified, concrete, iron or steel pipe be used will depend, to a certain extent, upon the relative cost of these materials in the particular locality where they are to be used. Vitrified, or concrete pipe, with joints laid in cement mortar, make a very satisfactory culvert.

For large openings, say those exceeding 5 or 6 ft. in diameter, culverts should, in most cases, be constructed of solid masonry, either stone or concrete. During the last few years, or since 1905, satisfactory structures of this kind have been made of reinforced concrete, the reinforcement permitting the reduction of the thickness of the walls and greatly reducing the quantity of concrete required and corresponding cost of the structure (Fig. 27).

In the design of all culverts, especial care must be exercised to see that they are of sufficient strength to carry the weight imposed upon them by the embankment above. Another essential, especially in culverts under canals or waterways, is that they shall be water-tight. Seepage along culverts should be guarded against by the construction of ample cut-off or curtain walls. Where a culvert is designed to be operated under a head, these cut-off walls should be carried entirely around the culvert. Approaches to culverts should be protected by wing and curtain walls and the bottom and sides of the channel should be paved. Where there is a material change in the shape of the cross-section from a canal to a culvert such change should be made gradual in order to reduce, so far as possible, the amount of friction and entry head required.

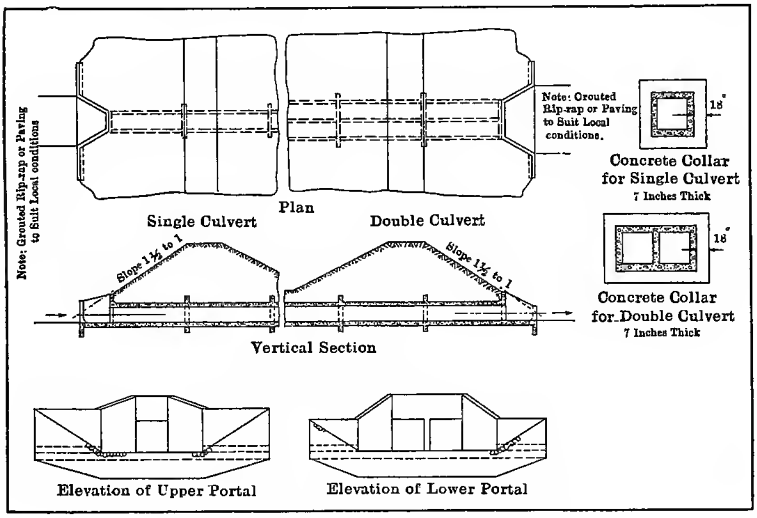


FIG. 27.—Reinforced concrete culvert.

Flumes.—Where topographic conditions are such as to make ordinary canal construction impracticable, flumes are frequently used. In general, flumes may be classified as bench and trestle flumes.

Bench flumes are used on side hill work where the slopes are too steep or the material unsuitable for an open canal. The foundation for such a flume is excavated in the side of the slope and should be level transversely and have approximately the same grade as the flume horizontally. The important points to be considered in preparing the foundation to receive the flume are : (a) Security against unequal settlement in the foundation; and (b) security against injury to the flume by slides of rock or earth.

Bench or side hill flumes should be supported upon natural materials when practicable, the excavation being made somewhat wider than the flume. Where, on account of the excess cost of excavation, as is sometimes the case on steep, rocky slopes, it is uneconomical to excavate into the slope wide enough to receive the flume, the lower edge of the bench should be built up of rock or masonry to make it secure against settlement. As a general rule, flumes should not be supported upon an earthen foundation part in cut and part in embankment, as the embankment portion is almost sure to settle. Foundations for bench flumes, especially if they be of earth, should be carefully drained to care for seepage and storm water carried down over the slopes. The drainage water should be collected along the upper edge of the bench and carried across it at frequent intervals in well-protected channels. Where large waterways are crossed on the slope the flume should be carried over them by means of trestles or suitable spans in order to leave ample waterways below.

The excavated slopes above the bench should, for the sake of economy, be made as steep as they will safely stand. The degree of steepness will depend partly upon the character of the materials and partly upon climatic conditions. Especial care should be exercised to see that all masses of rock which are partly loose are removed. In choosing the location for a side hill flume care must be exercised to see that the location is a sufficiently safe one that, with reasonable care and attention, the flume can be continuously maintained and operated.

Trestle flumes are used for carrying canals across depressions. One of the principal questions to be determined in connection with their use is that of feasibility. This should be determined by carefully prepared estimates of the various plans by which the work can be accomplished. In making such estimates weight must be given to permanency and cost of future maintenance, as well as to initial cost. For example, a canal constructed in an embankment of suitable material, even though its first cost exceed that of a flume, might eventually be far cheaper on account of its permanent character and low cost of maintenance.

Conditions are occasionally so much in favor of a particular kind

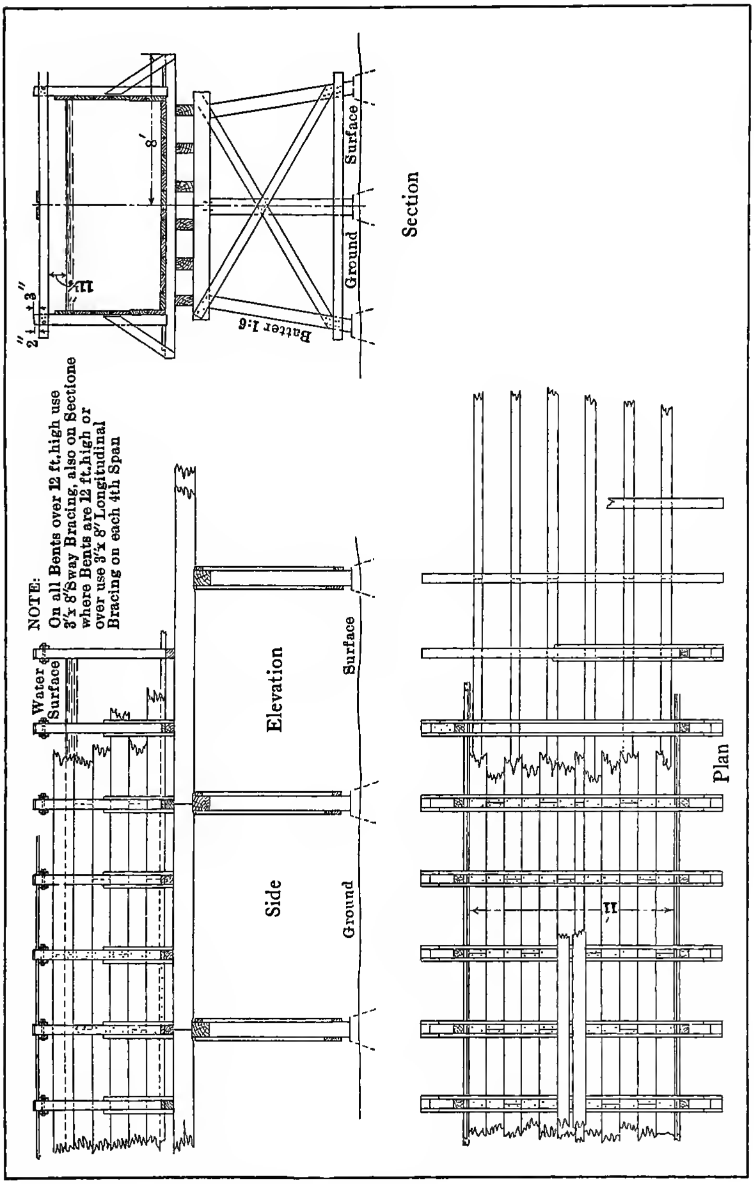


FIG. 28.—Typical plan for wooden flume.

of construction that comparative estimates are hardly necessary, while in other cases careful and detailed estimates are required. Where first costs do not differ materially, preference should be given to the plan which is most permanent in character and requires the least expenditure for maintenance. It is often necessary to consider also the amount of water losses. For a tight flume the losses by seepage and evaporation evidently will be less than from an earthen canal constructed of more or less porous material. For this reason, flumes are sometimes used to reduce seepage and evaporation losses.

In constructing a trestle flume, the foundation is of prime importance. If a trestle be of wood (Fig. 28) or other perishable material, it should be placed upon masonry carried well up above the surface of the ground. On account of the possibility of the ground under a flume becoming saturated, excessive loadings may cause settlement and should be avoided. Where possible, drainage for foundations should also be provided. In high trestles, wind pressure should be considered and the structure made safe against overturning from this cause.

The materials in the United States available for flume construction and within reasonable limits of cost are wood, metal, and concrete. Wooden flumes can be built for the lowest first cost in many sections of the arid west where timber is comparatively cheap. On account of the perishable nature of wood, however, the life of a flume of this character is short and maintenance charges, especially after the first few years, correspondingly high. Flumes are usually wet only a portion of the year and the alternate action of water and sun upon lumber has a tendency to warp and crack it, so that it is difficult to maintain a wooden flume in a water-tight condition. For the above reasons wooden flumes are not entirely satisfactory and their construction should be avoided if possible.

A type of flume used quite largely and one which has given satisfaction is a metal waterway supported upon a trestle or foundation of wood. These metal flumes are now manufactured from plates of comparatively pure iron, which it is claimed is less affected by corrosion than ordinary iron or steel. The accompanying Fig. 29 gives the principal dimensions of one of these metal flumes, supported on wooden trestles and provided at the ends with concrete inlet and outlet. A view of such flume in use is shown in Plate VII, Fig. D.

Reinforced concrete flumes have been constructed in some localities. On account of the lasting qualities of this material it is prob-

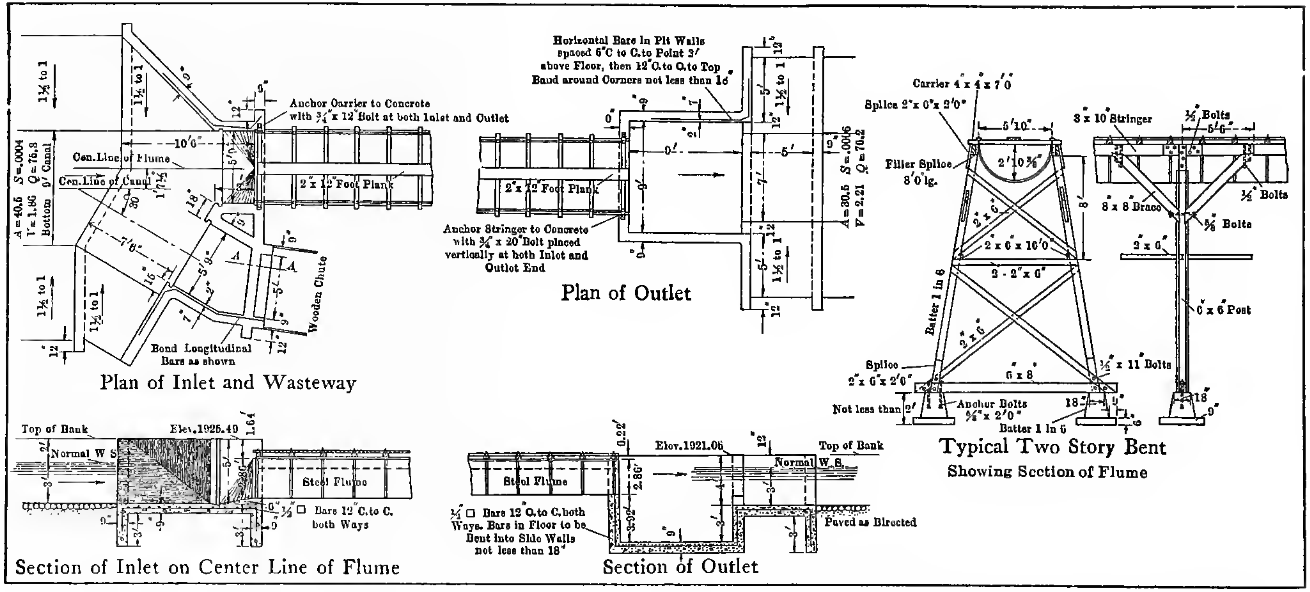


FIG. 29.—Steel flume, supported on wooden trestle, with concrete inlet and outlet, Lower Yellowstone Project, Montana.

able that the life of such a flume will be many times that of one built from wood or metal. The first cost of concrete flumes is relatively high but their superior lasting qualities and low maintenance costs seem to entitle them to consideration from an economic standpoint. (See Plate VII, Fig. A.)

In wood and metal flumes the waterway or lining should be so constructed that it can be replaced without disturbing the main structure. This permits of repairs being readily made to the lining which ordinarily fails first. Various plans have been tried with more or less success for making the joints of wooden flumes water tight. The most common form of joints are caulked, battened and loose splined. Of these it is believed that splines are the most satisfactory in producing a joint secure against leaks. In a joint of this kind the thickness of the spline should be the same as the width of the groove and the width of spline slightly less than twice the depth of the groove. The latter precaution is necessary to prevent the spline being split when the planks of the lining are driven together.

Where a flume joins an earthen embankment especial care must be taken to prevent the current cutting around its ends since water has a tendency to follow a joint between earth and a hard or smooth material such as wood or concrete. One of the best methods of preventing this erosion around the ends is to enlarge the ends of the flume for a distance of 15 or 20 ft. and carry the earthen embankment into these enlarged ends. That portion of the flume into which the earth filler is carried should have its floor depressed to a depth of 2 or 3 ft. below the grade of the canal and its side walls carried well out into the center of the canal embankments. A curtain wall should also be carried down at the ends of the flume (see Fig. 29). The bottom and slopes of the canal for some distance from the ends of a flume should be protected by means of rock or other form of paving. This paving, if constructed with rough surface, tends to check the velocity of flow along the sides and bottom of the canal and reduces the chances of erosion.

Velocity and Flow of Water in Flumes.—In order to reduce the size of a flume to a minimum, the velocity of flow in it should exceed that in the canal. Flumes are generally of material that will stand high velocities without danger of erosion; the velocities which may be attained in them are usually, however, limited by the grades available and the checking of the flow at the lower end of the flume rather than by the velocity which the material will stand.

The velocity of flow in a flume may be computed from the slope,

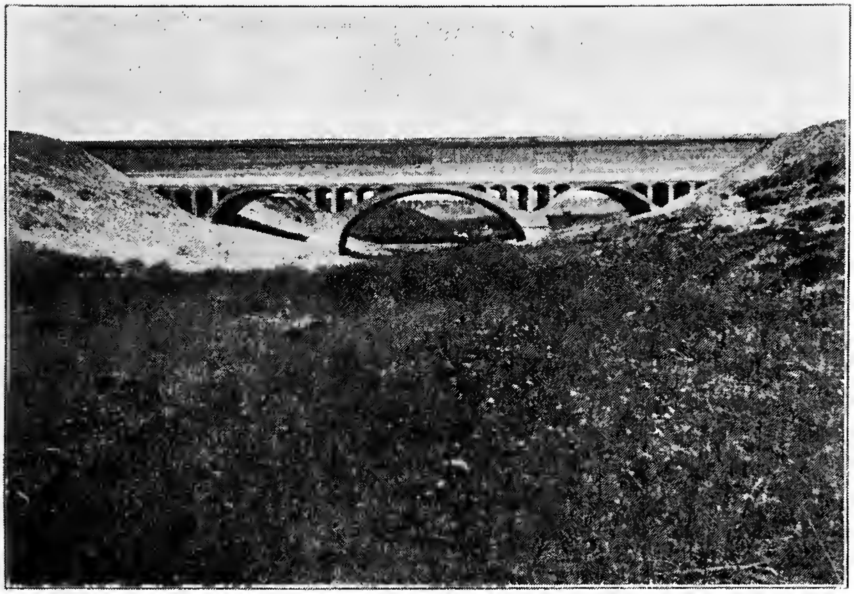


FIG. A.—Concrete flume carrying water of main canal across side drainage lines. North Platte Project, Wyo.-Nebr.

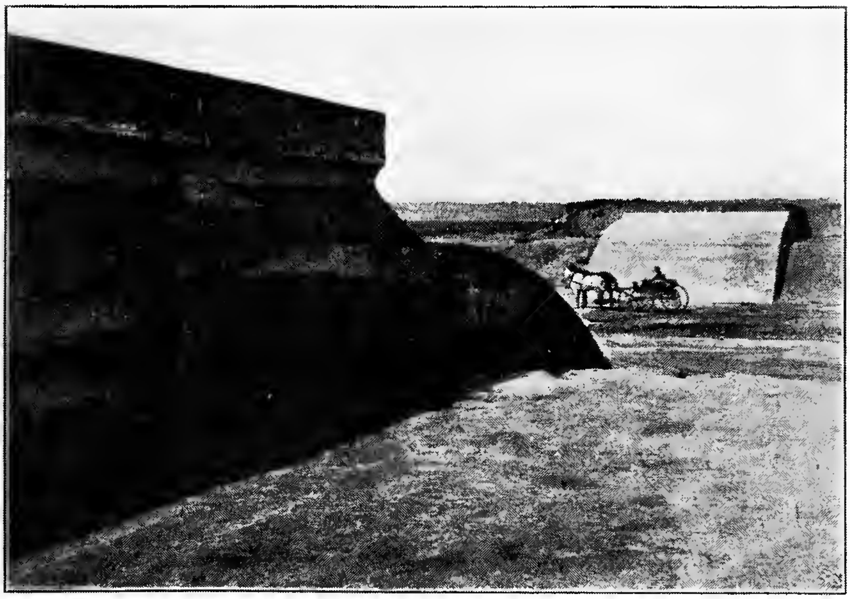


FIG. B.—Concrete inverted siphon carrying water of main canal under side drainage line instead of over it. North Platte Project, Wyo.-Nebr.

FIG. C.—Concrete pressure pipe used in place of flume. Sun River Project, Mont.

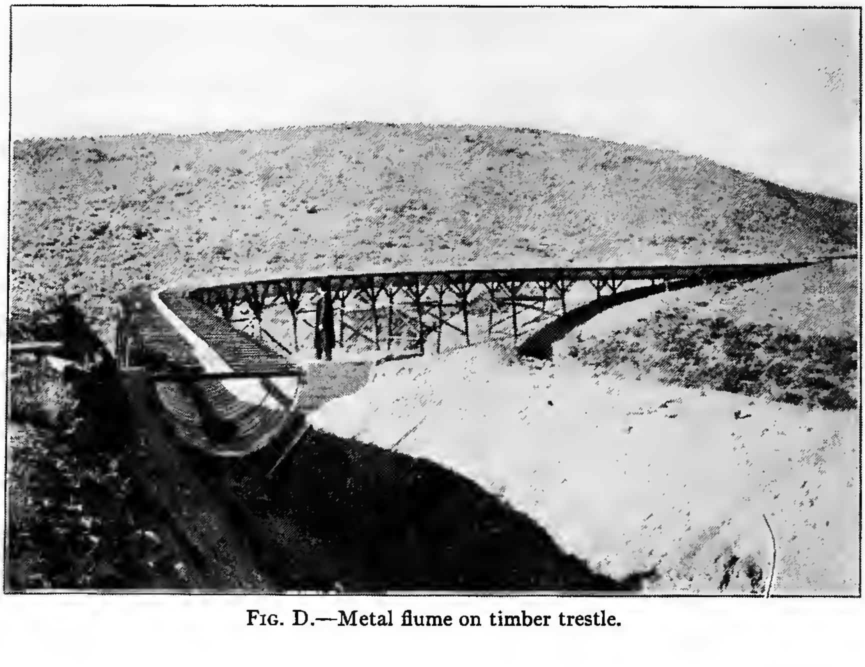


FIG. D.—Metal flume on timber trestle.

hydraulic mean radius, and an assumed value of "*n*," the same as for open canals. Where the velocity in a flume exceeds that in the canal above there must be sufficient drop at the upper end of the flume to provide for entry and increased velocity heads. The value of the entry head will depend upon the form of transition curves from the canal to the flume section and may ordinarily in practice be made so small as to be negligible. The increased velocity head is the head corresponding to the velocity in the flume, less the head corresponding to the velocity in the canal above. Calling its value h it may be obtained from the expression $h=\frac{V_1^2-V_2^2}{2g^2}$, where V_1 equals velocity of flow in the flume, V_2 equals velocity in the canal above and g equals the acceleration of gravity in feet per second. At the lower end of a flume, where the velocity is reduced to that of the canal, there is a slight gain in head due to the water giving up a part of its kinetic energy. Theoretically it is possible to regain the greater part of this increased velocity head when the velocity is reduced; practically, however, it is not possible to regain but a small amount of it.

On account of the resistance of change in direction, flumes intended to carry water at reasonably high velocities should be free from sharp turns or reduction in grades. If these be introduced there is a tendency for the water to pile up at the point of change and possibly overflow the sides of the flume.

Tunnels.—A tunnel in connection with irrigation works is that portion of a canal or outlet of a reservoir which passes underground or pierces projecting ridges. The tunnels on the main-line canals are necessitated by the fact that, especially near the heads of the canals where they leave the river, the ground is frequently very rough and open cuts are difficult if not impossible to construct and maintain. Under these conditions, the most economical form of construction is to continue the canal by suitable excavations into and through the solid rock or partly consolidated earth, holding this in place if necessary by temporary timbering to be replaced later by permanent lining. In several instances tunnels of considerable length have been built through a mountain range or plateau to bring water from a distant river. The most notable of such tunnels is that on the Uncompahgre Valley project in Colorado over 30,000 ft. long taking the entire summer flow of Gunnison River and the tunnel of the Strawberry Valley project, Utah, over 22,000 ft. long, the other dimensions of which are given in Fig. 30.

This takes the water stored in Strawberry Valley through the top of the Wasatch range.

In planning tunnels not only should the first cost be considered, but more than this the expense of future maintenance of such tunnel as compared with an open cut. The latter, especially on steep hill sides, is exposed to many dangers; either it may slide out as a whole aided by the weight of the water and by the softening of the material, or it may be filled, in whole or part, by earth and rock sliding in from above. Thus the construction of a tunnel is often justified even though the first cost is larger than that of an open cut.

Experience in operating and maintaining finished canals is demonstrating that as a rule a considerable portion of the canal which has been built in very rough ground might have been more economically placed in tunnel, because the latter when once properly constructed is relatively permanent. The tendency is therefore to construct canals more and more in tunnel than in the past and in case of doubt in poor locations to throw the conduit underground rather than attempt to keep it wholly on the surface.

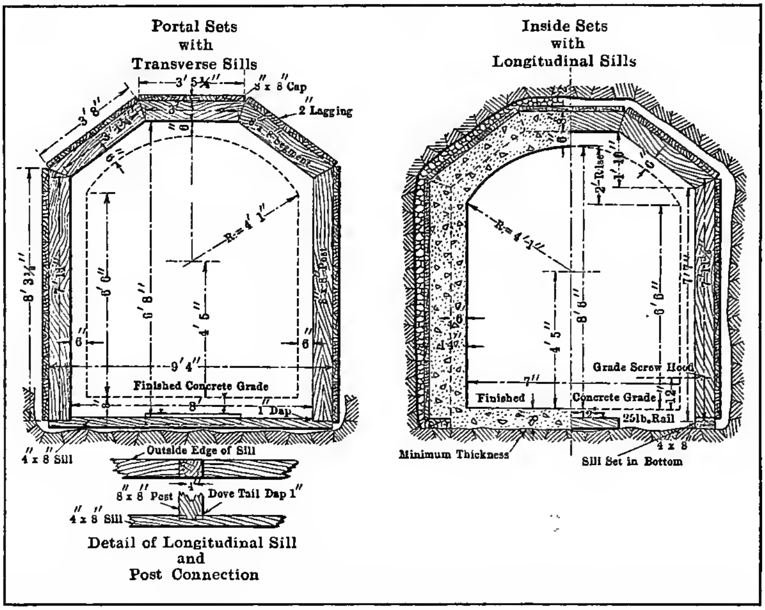


FIG. 30.—Concrete lined tunnel, Strawberry Valley Project, Utah.

Tunnels may be built of the full size and capacity of the canal or for economy of construction, the cross-section may be reduced. In the latter case, it is obvious that the velocity through the tunnel must be increased by giving it additional grade and the approach to the tunnel must be so designed as to provide sufficient velocity of entrance to permit water to the entire capacity of the canal to pass through the tunnel. This latter feature has been neglected on some notable works and the tunnels when finished have been found to obstruct the flow so greatly as to necessitate expensive changes.

The decrease of the section of the tunnel and consequent increase in slope results in the canal descending somewhat rapidly and thus losing the advantage of elevation in commanding irrigable land. If the descent of the ground from the intake of the canal to the irrigable land is so great that there is ample grade allowable without sacrificing irrigable area, then it follows that heavy grades can be given to the tunnel and corresponding reduction of cross-section. But if, on the other hand, the area of irrigable land is limited by the elevation to which the water can be delivered, then it may be necessary to keep the size of the tunnel, to the full area of cross-section of the canal thus reducing the slope and keeping the canal at the highest practicable elevation. These balancing considerations should be taken into account in all designs of canals where tunnels are used.

The construction of tunnels may be considered as almost a distinct branch of engineering, especially those in soft ground where great skill must be employed in holding the roof and walls. For the present purpose, it is sufficient to call attention to the fact that in all tunnel work there necessarily exist great uncertainties as to the conditions to be encountered and the probable time and cost of completion. As part of the preliminary survey and examination, borings should be made at short intervals along the proposed route and all possible facts obtained as guidance in preparing preliminary estimates and plans and specifications. Even with the most thorough exploration by drill holes and other methods such as are feasible under the circumstances, there are still considerable risks to be run and a large contingent expense must be allowed.

Lining.—Lining must usually be provided for tunnels of this character not only to prevent the top and sides from falling in but also to reduce the friction and increase the capacity of the tunnel by providing smooth walls. It is usually necessary to set timbers to hold the roof and in many instances it is not safe to remove these timbers; thus they are left in place being embedded in the permanent concrete lining. In extreme instances, it has been found necessary to use iron plates bolted together to hold the soft materials from falling into the tunnel and in these cases also this temporary lining is not removed but is covered by the concrete.

Where the walls and roof are of solid rock with no apparent tendency to disintegrate the tunnel is usually excavated as nearly as possible to the prescribed dimensions or neat lines and finished up to the true dimensions by a relatively thin lining of concrete, the voids between the concrete and the rock being filled with small stone. For this purpose, forms of wood or of metal are provided and are drawn through the tunnel on suitable tracks or other devices, being taken out and advanced as rapidly as the concrete sets.

Where the lining will be subject to heavy pressures the thickness is increased and all spaces filled in with concrete or stones embedded in it. It is highly desirable to preserve a smooth finish and to have the interior of the tunnel free from roughness which will tend to check the velocity of the water.

Inverted Siphons.—An inverted siphon or "siphon" as it is more frequently termed, is used for conducting water across depressions or under streams. It consists of a water-tight pipe or conduit usually laid below the surface of the ground and through which water is carried by gravity. Siphons take the place of trestle flumes in crossing depressions or streams. The question as to which method of construction is most feasible depends for answer upon local conditions in each particular case. (See Plate VII, Fig. B.)

The accompanying Fig. 31 gives the principal dimensions of one of the similar reinforced concrete siphons for carrying a distributing canal under a roadway on the North Platte project in Nebraska.

Siphons are better adapted to the crossing of deep ravines or canyons than flumes on account of the impracticability and cost of constructing and maintaining high trestles. They are also better adapted to carrying a canal across a stream of varying depth since they permit the water in the canal being carried at any elevation, while if carried by a flume it must be kept above the high-water elevation of the stream. In general, siphons are susceptible of more permanent construction and require less expense for operation and maintenance than trestle flumes.

In the design of a siphon it is necessary first to determine the amount of pressure or head to which it will be subjected, the fall available in its length and the character of the material in which it

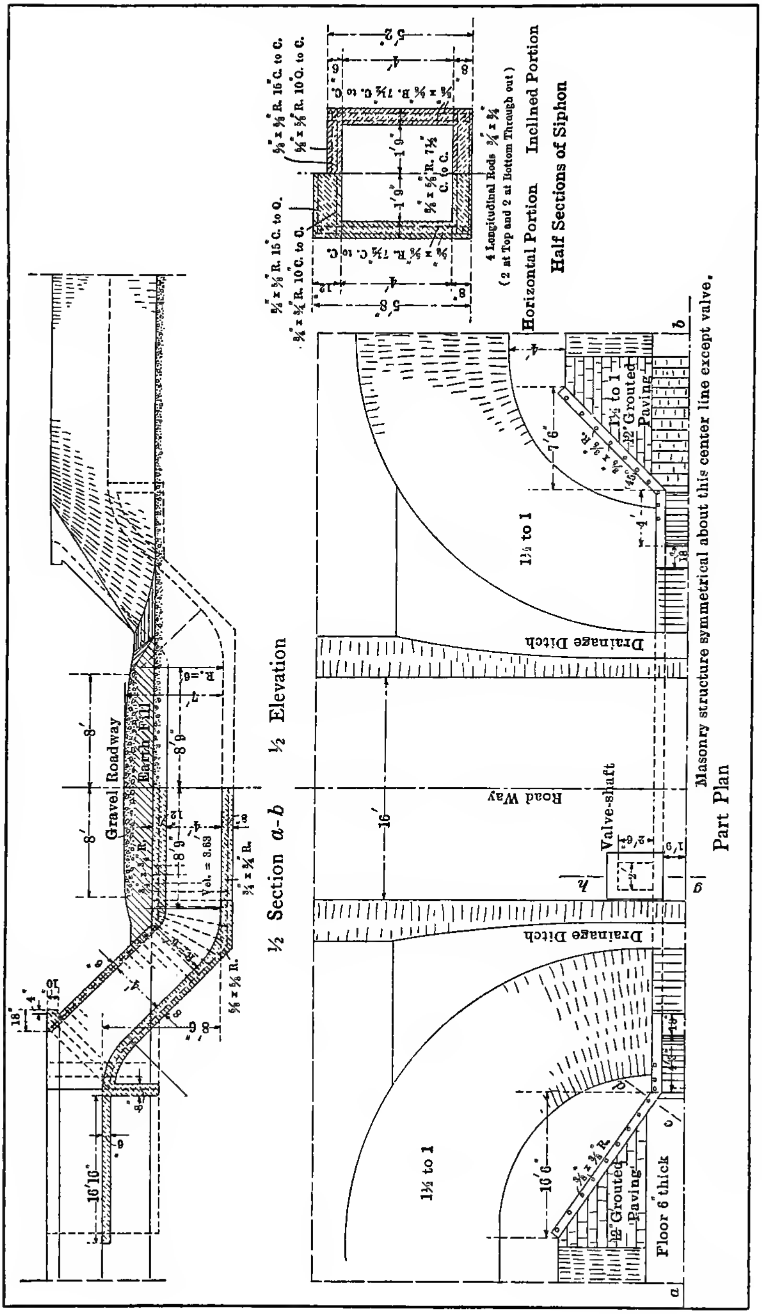


FIG. 31.—Reenforced concrete siphon for carrying canal under roadway, North Platte Project, Nebraska.

is to be constructed. The first two are necessary to arrive at the strength and size of conduit to be used and can be determined from a profile of the line. A knowledge of the character of material is necessary to enable the selection of proper foundations and anchorages for holding the conduit in place, and should be obtained by careful field examinations and excavations if necessary.

The head on any point of a siphon is the distance from that point, measured vertically, to the hydraulic gradient between the intake and outlet of the siphon. If this distance be expressed in feet the pressure p in pounds per square foot is $p=62.5\,h$. If the diameter of the pipe is d, the transverse stress, s, in pounds acting upon 1 lineal foot of the wall of the pipe and tending to rupture it is $s=62.5h\frac{d}{2}\cdot$ From this the strength of pipe or conduit required is readily computed.

The available head tending to overcome friction and produce flow in the pipe is the difference in elevation between the water surfaces at the two ends of the pipe. The head per unit length of pipe is this difference in elevation divided by the length of the pipe. From this the velocity of flow can be computed by the ordinary formulæ for the flow of water in pipes, allowance being made for velocity and entrance head. In order to obtain the maximum capacity of a siphon there should be a depth of water in the canal or entry chamber over the entrance to the pipe equal to the sum of the velocity and entry heads. Or the upper end of the pipe may be made of larger sections than the remaining portion.

The foundation under a siphon should be sufficient to insure safety against settlement under the combined load of the siphon and the water which it carries. It should be firmly anchored in place in order to prevent disturbances which would have a tendency to cause leaks, and if laid under a stream it should be well below the shifting bed of the stream. The depth to which a siphon should be placed below the surface of the ground outside of the stream bed or whether or not it should be covered at all will depend upon local conditions. A covering of earth, if made heavy enough, will prevent freezing during extreme cold weather and tends also to minimize the changes in temperature throughout the year and thus reduce contraction and expansion. Where siphons of concrete or metal, which have an appreciable coefficient of expansion are subjected to considerable changes in temperature, they should be provided with expansion joints at frequent intervals. All siphons, where possible, should be provided with means for emptying them for purposes of examination and repairs when necessary.

The materials from which siphons are commonly constructed are wood, steel, or iron, and masonry, including plain and reinforced concrete.

Wooden siphons are commonly constructed in the form of wood stave pipe, the necessary strength to resist the pressure imposed upon them being given by iron or steel bands. The size and spacing of these bands are dependent upon the size of pipe and the amount of head upon it. Siphons of wood stave pipe are being operated under heads of 100 ft. or more. On account of the wood staves being saturated with water they are not subject to decay to any marked degree, so that the life of such a siphon is practically the life of the metal bands.

Siphons of steel or wrought iron may be used under any desirable heads, cost being practically the only limit. For extreme heads, say from 200 ft. upward, these materials, on account of their high tensile strength, seem to be the most practicable. In using steel or iron pipes it is customary to cover them with some form of coating, such as coal tar or asphaltum compounds in order to protect them from corrosion. A siphon recently constructed by the United States Reclamation Service on the Uncompahgre Valley Project, Colorado, is made of practically pure iron. This siphon is approximately 3,700 ft. in length, 26 in. in diameter, and is subjected to a maximum head of about 200 ft. Pure iron was used upon the theory that this material will better withstand the corrosive action of certain alkali salts contained in the soil in which the pipe is laid.

Masonry siphons, except when reinforced, are practicable for low heads only. Reinforced concrete siphons have been constructed and are being successfully operated under heads up to about 100 ft. In constructing reinforced concrete siphons especial care must be taken to make a dense, non-porous concrete, in order to prevent leakage. Additional water-tightness can also be obtained by plastering the interior of the pipe with a rich mortar of cement and sand. Sufficient steel reinforcement must be used to withstand the entire water pressure with a reasonable factor of safety.

A combination of tunnel and siphon is occasionally necessary in connection with large irrigation works. One of the most notable examples of this kind is the tunnel under Colorado River near the town of Yuma, Arizona, where the main line of the irrigating canal is taken out on the California side, flows southerly to a point opposite Yuma, and then is carried under the river by means of a tunnel, water rising on the Arizona side, and continuing in the main line, with slight loss of head. There thus results a tunnel under pressure which is in effect an inverted siphon shown in Fig. 32.

This tunnel was driven through partly indurated sands beneath the bed of the river by the use of compressed air; it is nearly 1,000 ft. in length and 14 ft. in side diameter. Similar less expensive tunnels are occasionally necessary in passing under the beds of streams, but as a rule these are built in the arid regions during the time of year when the streams are dry, or the flow is so small that it can be carried in a flume across the point of construction and the tunnel built in the open. Still smaller structures which can hardly be termed tunnels are frequently built to permit the passage of canals under a depressed railroad track, or in other localities where it is not practicable to carry the water on grade.

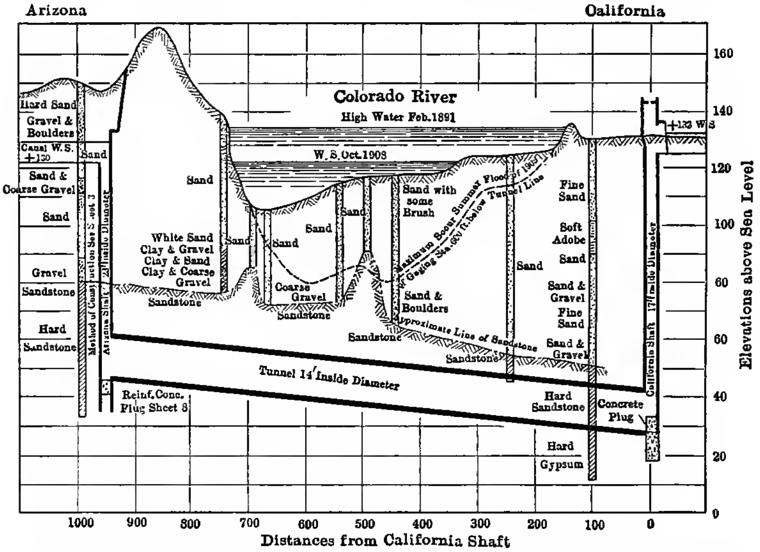


FIG. 32.—Vertical section of siphon or tunnel under Colorado River, Yuma Project, Arizona.

Bridges.—Where canals are constructed across public or private roads, so as to interfere with ordinary transportation, bridges must be provided. Whether or not these structures are built by public or private interests, or by the owners of a canal system, are matters of detail which may vary in individual cases. It must be recognized, however, that they are necessary and sooner or later must be constructed. By whomsoever built, provisions should be made that a type of bridge be adopted that will not interfere with the operation and maintenance of the canals. In order to accomplish this in a satisfactory manner the designer of a canal system should also provide, or at least approve, the plans for bridges which may be constructed across it.

Aside from the general appearance of a bridge, which is an item worthy of consideration in a prosperous community, the principal point for consideration is that they shall not interfere with the flow of water in the canal. To insure this they must be constructed well above the maximum high-water surface. A safe rule to follow in this is to make the height of the bottom of the floor system above the maximum water surface equal to the free board of the canal. On large main canals, where bridges of considerable lengths are required, the question whether piers or center bents may be constructed in the canal or whether a clear span should be used depends upon local conditions. If a canal carries large quantities of silt or dèbris, any obstruction is likely to prove a menace to the free flow of water. Floating weeds, such as are found in many sections of the west, are especially dangerous and may obstruct the channel to such an extent that water will be forced over its banks. Where the water is clear and does not carry floating materials, center bents may be used without detrimental effects.

The kind of bridge to be used, whether wood, steel, or concrete, will depend upon the permanency of the structure required and the relative costs of the various materials in the particular locality. In the design of bridges consideration should be given to the maximum loads which they may be required to carry. This will depend upon the nature of the traffic and will vary in different sections. The maximum load on a public highway bridge should not exceed one-fourth or one-fifth of the ultimate strength of the bridge. All crossings over canals should be constructed in a manner not to interfere with free access along the canal.

Measuring Devices.—The amount of water diverted from the source of supply to the canals and also the amounts delivered from the canals for irrigation or other purposes, should be determined for the proper management of the system. The quantity drawn from a source of supply must be known in order to determine what is available for use and to properly conserve this supply. The various amounts diverted from the canal system must be known in order to ascertain how much is being delivered to water users under the canal and how much is lost or wasted. Whether water be disposed of at a unit price for a given quantity say an acre-foot, or whether it is paid for in terms of the area irrigated, a knowledge of the quantities delivered is essential.

In order to determine the amount of water diverted to and from a canal system each diversion structure should be provided with some means of ascertaining the amount of water which it delivers. In this connection it is well to state at the outset that water measurements under the conditions that exist in practical irrigation are liable to serious inaccuracies and that improvement in this particular branch of irrigation work is urgently needed. The inaccuracies of our present methods, however, do not justify their neglect nor discontinuance.

In general, measuring devices for use on canals may be brought under four classes; namely, submerged orifices, weirs, rating flumes, and mechanical meters. The factors involved in the use of submerged orifices are the size of the orifice and the head upon it. Where a constant head can be maintained fairly accurate results can be obtained, the difficulty, however, is to maintain this constant head. This method of measurement is commonly used to determine the amount of water passing large headgates, the quantity of discharge, Q, being computed from the formula $Q=AC\sqrt{2gh}$. Where A is the area of opening, g the acceleration of gravity in feet per second, h the head, and C a constant depending upon the shape of the opening. Submerged orifices are also sometimes used to determine the amount of water diverted into small canals, the head being determined by taking the difference in elevation of the water surfaces above and below the orifice by means of fixed gages. This form of apparatus has the advantage of not requiring any considerable amount of fall and can be used where it is necessary to hold up the water surface in order to cover the maximum area of land. Where low heads are used the results computed from head and area of opening are subject to considerable error.

One of the most convenient and accurate methods of determining the discharge into a small canal is by means of a weir. The depth of water flowing over a weir can be shown with reasonable accuracy by means of a gage and from the gage reading the quantity flowing can be readily determined. One objection to the use of weirs is that they require a loss of head from the main canal to the lateral equal to approximately the depth of water flowing over the weir. In exceptionally flat countries a drop of a few inches in the lateral may mean the loss of a considerable amount of land. For this reason it is not always practicable to install weirs at the head of laterals.

Weirs must be kept in good repair in order to obtain reliable results. The required conditions as to fall and contraction of the channel must be maintained, this usually requiring frequent attention. The smaller weirs are rapidly obstructed by silt, the bottom is built up and the end contractions are partly suppressed. Frequently the smaller canals or laterals below the weirs become choked, backing the water up on the crest of the weir. Continuous attention is required on the part of a well-trained force of canal men to keep these in proper condition.

A less accurate, but more simple method of measuring the flow is by means of a rating flume placed in the canal, whose waters are to be measured, a short distance below the head. This flume may be of either wood or concrete and its depth should be sufficient to carry the desired quantity of water. Its width is ordinarily about the same as that of the canal. The capacities of the flume for different depths of water are determined by calibration, that is, by measuring the discharges at various depths by means of a weir or current meter. Flumes, like submerged orifices, require but little head for their operation, and for this reason can be used where weirs are not applicable.

One of the chief objections to any of the above measuring devices is that no account is taken of changes in flow due to variations in the head of the canal. In order that these variations be shown it is necessary that they be equipped with self-recording water-stage registers, which, for a large canal system, are expensive, both to install and to maintain.

Mechanical meters consist of some form of revolving wheel which is operated by the current and whose velocity of rotation varies with the velocity of flow. The apparatus is placed in a contracted section of the canal, built of wood or masonry. The revolutions of the wheel are graduated in terms of the quantity of water discharged, either in second-feet or acre-feet.

A form of self-measuring apparatus now being tried on some of the projects of the United States Reclamation Service registers the amount of water delivered in acre-feet.

In the use of the various forms of water-measuring devices much depends upon the ability, judgment, and skill of the persons using them. The essential thing in constructing a canal system is that some form of measuring device should be installed. The type selected for any canal system should be that best suited to the conditions which prevail on that particular system.

Screens.—It is necessary to screen the inlets to all pipes and culverts to prevent floating material being carried into them, and to exclude fish at the head of canals taking water from perennial streams. In the United States it is usually required by state law that fish screens be installed. The western states as a rule require that the bars of these screens be not more than 1/2 in. apart. This results in catching floating leaves, sticks, grass, and moss so that the screens are quickly clogged and the canal banks may be flooded unless the screens are watched constantly, or some automatic device is provided.

Screens should consist of nearly vertical bars without any cross bars near the surface which can catch the teeth of a rake or other tool used for cleaning. The most successful screen so far known is that consisting of iron bars 1/2 in. wide and 2 in. deep, arranged as a grill, inclined at an angle of one in four, and with a footway near the top from which the operator can work.

Protection of Canal Structures.—On account of the important functions of canal structures and the magnitude of the damage which may result from their failure, especial care should be taken for their protection. The principal causes of failure which must be guarded against are erosion and seepage. These causes are common to practically all classes of structures which are used for controlling or regulating the flow of water. The general principles applying to one case are, therefore, equally applicable to another.

Where the section of a waterway or canal is changed or where the velocity of flow is increased, one or both of which may occur at headgates, checks, drops, and diversion structures, there is a tendency to set up eddy currents or disturbances which may cause erosion of the sides or bottoms of the channel. This erosion may take place either above or below a structure and cause a dangerous condition to exist before it is discovered. To avoid this source of damages it is necessary first to so design structures that the variations from the normal canal section will be a minimum, and second to thoroughly protect the channel above and below them.

When water is carried over a drop an increase in the velocity of flow cannot be avoided. This increased velocity must be reduced at the bottom of the drop and the channel at that point must be sufficiently protected to absorb without danger the energy expended upon it. The same is true of water carried through turnouts under any considerable head, and it is necessary to guard against erosion at the points of entrance and discharge of these structures. A very satisfactory form of channel protection is rough stone paving laid on a firm foundation and the joints filled with concrete mortar. The advantage of rough stone is that it checks the velocity more effectively than a smooth paving.

Seepage along the sides and under structures should be guarded against by the use of ample cutoff walls, and by backfilling around all structures with impermeable material carefully puddled or tamped into place. The construction of projecting rings or collars on a turnout pipe will, to a large degree, prevent seepage water following along the outside of the pipe. Thin narrow buttress walls, carried up along the outside of a structure, will reduce the tendency of seepage water to follow around the structure. Embankments above structures, especially where wing walls are carried into them, in addition to being carefully constructed should be made of generous dimensions.

CHAPTER VI

DISTRIBUTION SYSTEMS

Canals and Laterals.—The term "Canal Systems" applied to irrigation works includes all channels used in conveying water from the source of supply to the point where it is ultimately delivered onto the land. The channels included in a canal system may vary greatly in dimensions and have capacities ranging from above 1,000 cu. ft. per second down to 1 cu. ft. per second or less. The various conduits or a canal system are usually classified under the general heads of canals, laterals or distributaries as the latter are sometimes called. The distinction between canals and laterals is, to a certain degree, an arbitrary one. In general, however, the term canal is applied to a channel which carries water for irrigation but from which direct diversion of water onto the land is not made. The term lateral is applied to a channel which takes water from the side of the canal and carries it along or near the canal and out onto the land to be irrigated.

Canals are further sub-divided into main and branch canals. A main canal is one which carries water directly from the source of supply. Branch canals, as the name implies, are those which carry water from a main to different irrigable areas. Laterals are also subdivided into main and branch laterals. The terms more frequently used, however, in this connection, are laterals and sub-laterals; a lateral being a channel which, in addition to distributing water from a canal directly to the lands, also conveys it to smaller branch or sub-laterals. The term "Distribution System" is intended to include channels which carry water from canals and distribute it onto the lands.

It is to be noted that the definition of canals and laterals takes no account of the relative capacities of these channels. A channel defined as a lateral may, therefore, have several times the capacity of another channel properly defined as a canal, *i.e.*, the main canal of a system taking water from a stream or reservoir to 10,000 acres may be smaller than the lateral of another system supplying 20,000 acres. or more.

General Plan of Distribution System.—The requirement of a distribution system is that it shall be capable of supplying water to all irrigable lands under the canals. In general, irrigable lands are divided into small areas or individual holdings, and an adequate distribution system is assumed to be capable of delivering water to the highest point of each of these small areas. The plan of a distribution system will depend upon the topographic features of the tract to be irrigated, and, in general, each system must be modified to suit peculiar conditions.

For irrigation requirements lands may be considered under three classes: (a) uniformly sloping planes, (b) ridges, (c) undulating areas, portions of which are higher than any other lands immediately adjacent to them. The problems met in planning a distribution system are those of reaching each of the above-described areas with a minimum amount of construction work.

Uniformly sloping planes allow great latitude of design in distribution canals and permit ordinarily the laying out of rectangular or parallel systems of laterals. Where possible these laterals should be located along land sub-divisions and property lines. This plan of location avoids the necessity of cutting across individual farms by canals and frequently reduces the amount of good land otherwise required for right-of-way for canals. Systems of this kind should have the laterals or sub-laterals near enough together so that water can be carried over the lands from one farm to the next adjacent to it. Where topographic conditions are favorable the area between two laterals may be covered partly from one side and partly from the other.

Ridges must be reached by laterals constructed along their highest portions. These laterals must necessarily conform to the direction of the ridges so that water may be carried from either side down the slopes to the intervening depressions. This necessitates an apparently irregular plan, the laterals crossing the fields.

Undulating areas are by far the most difficult to irrigate and no general plan is applicable for different cases. High spots above the level of adjacent lands may be reached by means of ditches or flumes built above the surface of the ground. Siphons or pressure pipes are also used to carry water across low depressions to the higher lands. The choice of one of the various plans which may be used for reaching isolated high areas ordinarily requires comparative studies of cost as well as consideration of their relative merits for permanency and efficiency.

The necessity of a carefully considered plan of works for the distribution of water cannot be too strongly insisted upon. The distribution system is to an irrigation project what a delivery system is to a transportation company in carrying on its business. If a distribution system fails or is inefficient, the entire irrigation system fails or is rendered inefficient to a greater or less degree. Mistakes made in the original planning and laying out of a lateral system ordinarily cannot be corrected without damage to improvements and a corresponding high cost for making changes. The ultimate value of an irrigation system depends upon its efficiency in supplying the needs of the water user.

Topographic Surveys for Lateral Systems.—On small areas, or areas the topography of which is comparatively simple, the most feasible plan for a lateral system can ordinarily be determined without extensive topographic surveys, the method followed being to determine the elevation of the commanding points on the area and using these as a basis for the location of the main laterals. In making these preliminary studies the principal point to be considered is to locate the main laterals so that they will command as much as possible of the irrigable area. In preparing plans in this manner alternate surveys should be freely made in order that all possible and feasible plans may be considered.

For large areas, or areas where the topography is complex, contour maps should be prepared as a basis for laying out lateral systems. The principal objection to a topographic survey for this purpose is its cost. One of the first points which must be decided is whether or not the topography is such that the advantages to be gained in the efficiency of the system are sufficient to justify the expense of such surveys. The advantages of topographic surveys as a basis for planning lateral systems are as follows: (a) They show the general slopes of the country, give at once the amount of fall which is available, and serve as a guide for the general direction in which laterals should be constructed. (b) On complex topography, such as broken ridges or isolated high areas, they indicate what lands can be covered by surface canal and those which must be reached by means of flumes or siphons. (c) Several alternate systems of laterals can be laid out on a carefully prepared contour map and preliminary estimates made thereon, at a much less cost than these studies can be carried on in the field, and the individual areas into which a tract must be broken in order to reach all points can be readily determined. (d) Topographic surveys, in addition to being an aid in the designing and locating of a lateral system, are of benefit in future maintenance as they indicate, in a general way, how irrigation can best be carried on after the system has been constructed.

Where the topography is such as to permit of various plans being used the cost of a topographic survey of the lands to be covered is justified, and, in most cases, there is an actual saving by this procedure, due to the more economic method in which engineering studies can be made and the greater efficiency of the system that can be designed. In working from topographic maps the engineer has before him, in condensed form, the entire irrigable areas and is thus enabled to project thereon all possible plans. In working directly from the ground, it is impossible, especially if the topography is complex, to see all of the various methods which may be used and some of the most advantageous features of a design may be overlooked.

Topographic maps to be used for designing a lateral system should be constructed on a sufficiently large scale to enable the various works to be projected thereon. The contour interval should be small enough to enable one to determine from the map, to within a reasonable degree of accuracy, the courses of the various laterals, the location of drops and other structures, as well as the areas which can be brought under any particular lateral. The scale and contour interval best adapted to a particular case will depend upon the nature of the country, the most complex topography requiring the smaller contour interval and larger scale. In general, maps to be used for lateral locations should have a contour interval not exceeding 1 ft., and a scale ranging from 400 to 1,000 ft. per inch.

Where contour maps are prepared for aid in designing a lateral system, attention should be given to other features which will make them valuable for future use in connection with operation and maintenance work. The contours should be projected upon an accurate base map, which should show, in so far as they can be located, the positions of all public and private land lines and corners.

Capacity of Laterals.—The discussion of capacity of canals, given on page 39, applies also to laterals and distributaries. In the design of the smaller distribution canals, however, some factors must be given consideration which are insignificant and may be omitted for larger canals. One of these already mentioned is that of the maximum duty of a canal. A canal which is used only a portion of the time, as is commonly the case with a small lateral, must have a greater capacity per unit area of land covered by it than one which is operated continuously. Other and equally important factors in small laterals are evaporation and seepage losses.

Evaporation losses from small bodies of water, climatic conditions being practically the same, will vary almost directly as the area of water surface. The percentage lost from a small canal on account of its less depth will exceed that from a large canal. Evaporation losses from the direct water surface in canals are, however, relatively small compared with seepage losses. The proportion of water lost by seepage is also much greater in small than in large canals. The results of observation on this subject, while not conclusive, seem to show that the average seepage losses from canals carrying more than 100 cu. ft. per second is less than 1 per cent. per mile of canal, while for canals carrying less than 10 cu. ft. per second the average losses exceed 10 per cent. per mile. On account of the higher seepage losses the allowance made for them in fixing the capacity of a small lateral must be relatively much greater than for a large canal. Just what these losses will amount to in any particular case will depend upon the character of the material forming the waterway of the canal. It must be remembered, however, that seepage losses are constantly taking place from earthen canals and that while the percentage of loss may be so small as to be negligible in very large canals it may be sufficient to materially effect the capacity of a small lateral.

Some investigations have been made to determine seepage losses in terms of the wetted area. These results show losses varying from about 0.25 to 6.0 cu. ft. of water per square foot of wetted area per day. In most cases, however, the daily rate of seepage varies from about 0.5 to 1.5 cu. ft. per square foot of wetted area. Data on see page losses, in this form, are the most convenient for practical use in determining comparative losses in various materials. They can readily be reduced to a percentage of total flow per mile for any particular size and shape of canal.

An illustration showing the method of taking account of seepage losses may be of interest. Let it be required to deliver at the lower end of a lateral 10 miles long, water at the rate of 20 cu. ft. per second. Assume the seepage losses to be 3 per cent. per mile. How much water must be supplied to the head of the lateral? The safe and quick method of computing this would be: multiply the percentage of less per mile by the length of canal in miles, which gives a total loss of 30 per cent. This result is slightly in excess of the actual theoretical losses, since no account has been taken of reduced amounts being carried at each succeeding mile. The actual amount reaching the lower end of the lateral, computed upon the basis of 3 per cent. of that delivered to it being lost in each mile, is $0.\overline{97}^{10} = .737$ or 73.7 per cent. approximately. The quantity which must be delivered to the head of the lateral to supply 20 cu. ft. per second at its lower end is 20 divided by .737 $= 27.1$ cu. ft. per second.

The minimum amount of water by which irrigation can be effectively and economically carried on is sometimes called an irrigation head. It will vary for different kinds of soil and crops. In general, however, it may be said to range from 1 to 10 second-feet.

The capacity of a lateral, whatever the area under it may be, must be large enough to carry enough irrigation heads or sufficient water to permit of economic irrigation. In order to carry on irrigation economically and to get over the ground satisfactorily, sufficient water must be supplied to permit of a cultivated area or field between checks or ridges being entirely covered before that portion to which water is turned first becomes unduly saturated.

The growth of grass and weeds in laterals tends to materially reduce their capacity and should be taken into account when designing a distribution system. This reduction, while small in sectional area, in some cases may be sufficient to reduce the velocity and consequent capacity of a canal by as much as 40 or 50 per cent., thus rendering it too small to carry an effective irrigation head.

Location of Laterals.—The problems involved in the location of small laterals differs in some respects materially from those met in the location of larger canals. The principal function of a main or branch canal is to carry water from the source of supply to the smaller distributaries or laterals. The importance of main and branch canals as a part of a system demands that they be given the safest possible location which the nature of the country and reasonable limits of costs will allow. Since water is ordinarily not diverted from these canals directly to the lands it is unnecessary to carry them above the surface of the ground in order to reach especially favorable points for diversion.

The function of a distributary or lateral is to carry water directly to the irrigable lands. The location must be so chosen that the maximum area can be watered. Favorable points for diversion must also be considered and the laterals brought to them. The general elevation of laterals must be sufficiently high to enable the water surface to be kept above the adjacent lands. Where necessary in order to accomplish this the waterways of laterals must be constructed in embankment. In other words, the main object to be considered in lateral location is the delivery of water to the greatest possible area.

Safety against breaks in laterals should be insured by properly planned and constructed banks, rather than by reducing the amount of land under them to obtain a more favorable location. It is frequently necessary to compare the difference in the cost of construction over two different locations with the value of extra land which can be reached if the more difficult route be chosen. In making such comparisons it must be remembered that the value of lands, when once brought under irrigation, may be expected to continue to increase in value, and for this reason the greatest development possible should be considered.

On uniformly sloping areas, all of which can be watered by two or more systems of laterals, efficiency of system and economy of construction should be considered. These questions may involve the laying out of alternate systems and the making of estimates on each. On flat slopes, where the velocities are necessarily low there is usually an economy in serving as much land as possible from a single lateral, on account of the larger cross-section required and correspondingly higher velocities which may be attained.

Cross-section of Laterals.—In fixing the cross-section of a lateral there should be considered (a) the character of the material; (b) the method by which it is to be excavated, and (c) the grade or slope.

Lateral ditches are for the most part constructed in fertile soils which will not support steep banks. Ordinarily it is not practicable to construct slopes steeper than 1 to 1, and, except in very rare cases, is it necessary to make them flatter than 2 to 1. If laterals are built by means of teams and scrapers, slopes of 1 1/2 or 2 horizontal to 1 vertical are the most practicable from the standpoint of construction, since these slopes facilitate team work in taking out the excavation. If, on the other hand, the work is to be done by excavating machinery, slopes as steep as 1 to 1 may be found to an advantage. In permeable soils, where seepage losses are high, as steep slopes as possible should be used in order to reduce the amount of wetted area to a minimum.

The ratio of bottom width to the depth of water is an important factor in determining the velocity of flow. Where the land is nearly level and it is necessary to conserve grade as much as possible, a comparatively narrow and deep section is the most advantageous. Where the fall of the land is considerable and it is necessary to reduce velocities, much can be accomplished by adopting a wide and shallow section. In fixing the ratio of width to depth, account should be taken of the method by which excavation is to be carried on and also the character of the material for resisting seepage.

The top width of banks and their height above the water surface will depend upon the stability of the material of which they are constructed, and the degree of safety against overtopping which it may seem desirable to adopt. In general, the top width of banks, for the smaller laterals, need not exceed about 3 ft. The height above the water surface should be sufficient to give stability to the embankment and serve as a protection against overtopping in case of a sudden rise in the canal. It is not an uncommon occurrence for a lateral, especially a small one, to be required to carry temporarily an overload of 50 per cent. above its figured capacity and provisions should be made for such emergencies. Where the waterway is all, or a great part, in fill, a greater height of free board should be allowed than where it is in cut. This latter precaution is necessary to give stability and provide for settlement in the higher embankments.

Points of Delivery of Water.—The location of points where water is to be delivered from laterals and sub-laterals to the lands will be determined to a great extent by the topography of the lands to be irrigated. The fundamental requirement is that these points be so located that water can be carried from them over the maximum area by means of small farm ditches. The number of delivery points should be as small as possible and still provide ample means for reaching the entire irrigable area. By reducing the number of delivery points to the minimum required, the cost of construction, operation and maintenance of small diversion structures is reduced. In general, delivery points should be located on the highest lands possible, or in other words, where the laterals or sub-laterals are entirely or to a large extent in excavation. These higher points are as a rule more favorable for delivery of water to the lands and also for the safe maintenance of structures.

A condition which frequently arises to increase the number of delivery points of a lateral is that where the irrigable area is divided into small individual holdings, each requiring an independent water outlet. Such a system permits the amount of water turned to each user to be measured and controlled and prevents the necessity of water users making distribution of water among themselves. Delivery of water direct to each user, especially where lands are held in small tracts of from 10 to 20 acres, requires a much more elaborate and costly distribution system than where one delivery point can be made to serve an area of from 40 to 80 acres, or more.

The number of delivery points required depends upon the topography of the lands to be irrigated, the size of individual land holdings and the policy to be pursued in the delivery of water, that is, whether it is to be delivered to each individual or to associations of water users.

The question of fixing delivery points of a distribution system is one which requires careful study and consideration in each individual case, the fundamental principles to be worked out in these studies being to reduce the number of delivery points to the fewest practicable and still provide an efficient service for the entire irrigable acreage.

Delivery Box.—The term "Delivery Box" is usually applied to the structure which regulates and controls the distribution of water from the lateral to the land of the farmer. It is the last link in the system of canals and distributaries which carries water from the source of supply to the area upon which it is to be used. The requirements of a delivery box are that it be adequate to control and measure the water which passes it, and that its capacity be sufficient to deliver the maximum amount of water required for irrigating the lands under it. Various types of boxes are used in different irrigation systems and special forms are frequently devised to meet certain conditions. It is impossible to say that any one type is superior to all others. A fundamental principle which should be borne in mind is that delivery boxes are essentially a part of a canal system and should therefore be opened and closed only by the organization which operates the canal system. They should be so constructed that should it be found necessary, interference with them by unauthorized persons can be detected and prevented.

The amount of water delivered to the lands can be measured only at the point of delivery. It is therefore necessary that a delivery box be provided with suitable equipment for ascertaining the water which passes through it, if record of the amount used in irrigation is to be kept, as it should be in every case.

The simplest form of delivery box consists of a rectangular wooden structure placed in the side or bank of a canal or lateral and provided with an opening through which water is diverted. When not in use, the opening is closed by means of boards or some simple form of gate

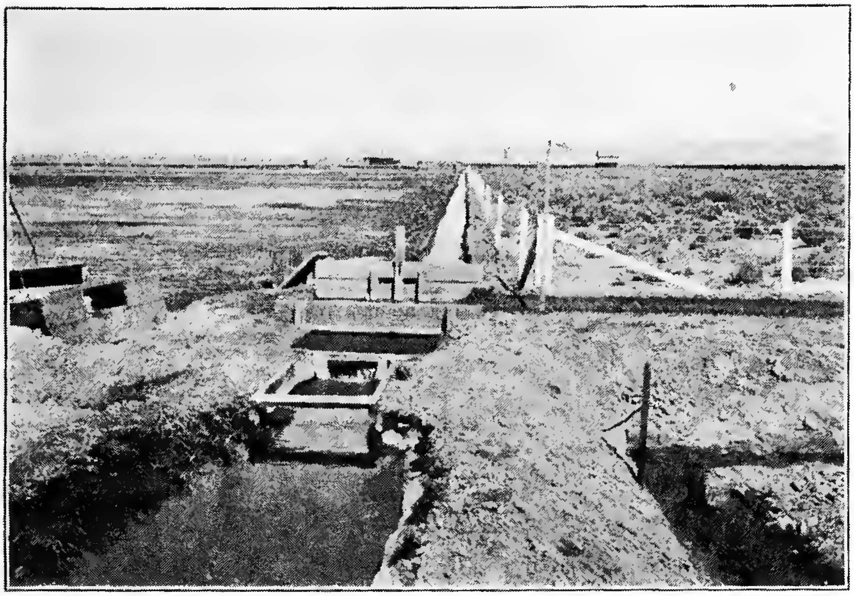


FIG. A.—Distributing laterals with wooden boxes and gates, typical of the pioneer work in irrigation. Yakima Project, Wash.

FIG. B.—Concrete box and drop on distributory in place of earlier form of wooden construction. Orland Project, Cal.

PLATE VIII

FIG. C.—Cast-iron valves on distributing systems instead of the usual wooden gates. Uncompahgre Project, Colo.

FIG. D.—Farmers' water gates on inclined concrete slabs. Sun River Project, Mont.

which can be raised to the required height to pass the quantity of water desired. More permanent structures of the same type are constructed of concrete or other form of masonry, and the openings closed by means of metal gates. Another type consists of a covered box of wood or masonry carried through the banks and having the upper and lower ends protected so as to prevent erosion. (See Plate VIII.)

The forms of measuring devices commonly used are weirs, rating flumes and some type of submerged orifice through which the flow of water can be determined. Where there is sufficient fall to permit its being used, the weir is perhaps the most satisfactory, cheap and simple device for measuring relatively small flows, such as are commonly turned into farm ditches and the smaller laterals and sublaterals. For this purpose both the rectangular and Cippoletti weirs are used (Fig. 33). The latter type of weir possesses some advantage over the former as it is unnecessary to take account of end contractions.

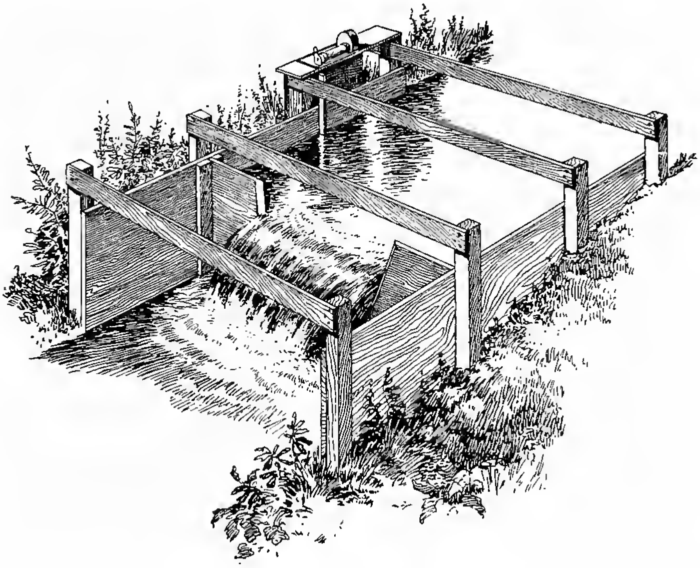


FIG. 33.—Plank measuring box with Cippoletti weir and automatic register.

A rating flume ordinarily consists of a square or rectangular box open at both ends and placed in the channel so as to form the waterway for a distance of several feet. The flume is first rated for various depths of water flowing through it by means of current depths of water flowing through it by means of current meters, weirs or other suitable measuring devices. For convenience of reference, the amount of discharge for different depths are commonly shown by means of a graphic curve or table. Measurements are then made by observing the depths of water passing the flume and taking the corresponding discharge from the curve or table.

A submerged orifice consists of an opening through which water is allowed to flow under a small pressure or head. The amount of head, if the orifice has a free discharge, is found by taking the height of water above its center, or if the lower side of the orifice be submerged, by taking the difference in elevation of water above and below the orifice. The amount of discharge depends upon the head, size of orifice and the form of the upper edge of the opening, whether square or round. The quantity of discharge Q may be computed from the expression $Q=AC\sqrt{gh}$ where A is the area of orifice, C a constant depending upon the form of the upper edge of the opening, g the acceleration of gravity in feet per second, h the head in feet. In order to determine accurately the amount of water passing a submerged orifice, the value of C for that particular form must be previously determined. Roughly, this value may be said to vary from about 0.6 as a minimum to 1.0 as an ultimate maximum. For a more complete determination of the flow of water through orifices, the reader is referred to special works on hydraulics.

Automatic devices for the measurement of water have been used to a small extent. They consist essentially of submerged orifices each provided with a current meter for measuring the velocity. These devices are commonly so graduated as to indicate the actual amount of water passed in some convenient unit of measurement, such for example as the acre-feet. In all measuring devices, unless they are provided with automatic registers, serious errors are apt to occur on account of variable heads, frequently found in the laterals. These errors in a great measure can be overcome for weirs, rating flumes and submerged orifices by the use of water-stage registers which show at all times the head in the canal.

The expense of refined measuring apparatus is usually large and it is frequently a question whether this is justifiable. The reply depends almost wholly on the value of water in the particular locality where they are to be used. For this reason in determining the type of measuring device, it is necessary to take the value of the water into consideration. In this connection, it should be borne in mind that water for irrigation is becoming constantly more and more valuable, and that while at the present time it is delivered through inefficient measuring devices, it is probable that within a few years, on account of the increased demands for water for irrigation purposes and its correspondingly increased value, careful measurements will be required. It is being more and more appreciated that in order to properly regulate the amount of water placed upon lands fairly accurate measurements of the quantity used must be kept. Wherever possible, therefore, as accurate means of measuring as are consistent with the conditions at hand should be provided.

Flumes and Pipe Distributaries.—In many irrigated sections flumes and pipes are commonly used instead of earthen channels for the smaller distributaries. The principal advantage of a flume or pipe over an earthen canal is the saving of water. They are also sometimes used on rough or undulating areas to avoid fills and cuts which would be necessary in constructing the small earthen channels. In very pervious materials, such, for example, as sand and gravel, it is impossible to carry a small quantity of water for any considerable distance in an earthen canal on account of the rapid absorption of water by the soil.

The smaller the quantity of water carried, in pervious materials, the greater is the relative effect of losses and the shorter the distance which water may be delivered. For example, in a channel carrying 50 or 100 second-feet, seepage losses which may amount to 1 or 2 second-feet per mile may be neglected, since they represent but a small percentage of the quantity of water carried. If, however, a channel carrying but 1 or 2 second-feet has the same rate of loss per square foot of wetted area in its channel, the entire quanity is soon absorbed.

Flume or pipe distributaries not only facilitate the flow of water and make irrigation possible on lands where it would otherwise be practically impossible, but they also result in large savings of water. These savings are sufficient in many cases to justify a large original outlay for their construction. Pipes, as a rule, are much more satisfactory than flumes, especially in warm climates where it is not necessary to protect them from freezing, either by careful drainage during the winter or by burying them to a sufficient depth below the frost line.

Wooden flumes are frequently used to cross low depressions, especially in the northern lands where lumber is relatively cheap. Wooden pipes are also sometimes used for this same purpose. These pipes are laid so as to act as inverted siphons under a small head.

Cement pipes are commonly used for distributaries in the intensively cultivated sections of southern California where the water supply is limited and where it is necessary to conserve it to the highest possible degree. These pipes are laid to a sufficient depth to insure their protection against the cultivation of the soil and are provided with frequent taps carried up to the surface from which water is discharged. They are constructed sufficiently strong to carry low heads and serve as pressure pipes where necessary to carry water across slight depressions in the ground. With a distribution system of this kind, little if any water need be wasted since it can be distributed from the pipes only at such points as required.

Accessibility to Laterals.—In designing and laying out a distribution system provisions must be made for easy access to all parts thereof. It must be borne in mind that even for the smallest canals which form a part of a system for the delivery of water they must be patrolled and operated almost daily. It is consequently of the greatest importance that the person in charge of operation and maintenance of these canals be unhampered in his efforts to reach them for this purpose. In order to properly maintain laterals, it is necessary that materials can be delivered to them quickly if necessary. In the event of banks being broken or washed away, earth for the repairs of the same is necessary, and provisions must be made for obtaining this material without delay.

The remarks heretofore made relative to rights-of-way for canal apply equally well to the smaller distribution canals, and no canal, however small, which is to form an integral part of a system and for which the owners of such system are responsible for its maintenance, should be constructed except on rights-of-way under their control. It matters not whether these rights-of-way be actually owned by an irrigation company or whether the right-of-way for the canal is simply in the form of an easement, the main question is that no one shall have any right to dispute the authority of the operators to enter on the right-of-way and operate and maintain canals in a proper manner.

Canal systems are built for the benefit and use of persons engaged in tilling the soil, and it is essential that these persons be unhampered in their farming operations by undue restrictions on access to their canals. This is especially true on small distribution canals which must of necessity cross irrigable lands. The coöperation of both the water users and the company or firm delivering the water is necessary. In order that this coöperation shall be effective, concessions must frequently be made by both parties, and any agreements for rights-of-way should be made specific enough to fully define the rights of each.

Conditions frequently arise where a small distribution canal must be constructed across private holdings in order to supply water to the lands of others. Such a canal is often a detriment to the person whose lands it crosses and may be unnecessary for his individual use. In such cases, it is absolutely necessary that no opportunity be given to this owner, should he be so inclined, to interfere with the delivery of water to the irrigators below. Right-of-way agreements in such a case should be so specific that it is not left to one individual to say whether or not his neighbor shall receive water.

The amount of right-of-way which will be required in individual cases, will, of course, depend upon local conditions. It is essential, however, that in every case there be sufficient to permit the canals to be operated and allow repairs to be made promptly when necessary. In general, it may be said that the rights of the people under a distribution system are paramount to the rights of any one individual, since it is only upon this basis that an irrigation system can be made a success. In other words, the individual cannot be allowed to retard the work of others on account of inconveniences to himself.

On the other hand, the individual, where land is crossed by a canal or lateral, is entitled to the protection in his rights and conveniences consistent with the rights of the people as a whole under canals. For example, the individual whose land is thus traversed is unquestionably entitled to bridge crossings which will give him free access to his land. Provisions must also be made for these crossings being maintained in such a manner that they will not interfere with the operation of the canal. The person or company responsible for the operation of the canal system must have access to all parts of that system. Such right of access, however, should not give them the right to unnecessarily inconvenience adjacent land owners.

It is impossible to lay down any hard or fixed rules as to exactly what should be acquired in the way of rights-of-way. Each particular case must be given due consideration in the planning of a distributon system and rights-of-way acquired so as to fully protect the interests of the individual whose lands are crossed, and also provide for the carrying on of operation and maintenance work in such manner as to make the system fully effective.

CHAPTER VII

IRRIGATION BY PUMPING

General Conditions.—It frequently becomes necessary for the engineer to consider the practicability of supplying water for irrigation by pumping. Conditions of this kind may be the result of the lands being situated at a higher elevation than any available water supply, thus making irrigation by gravity impossible, or it may be that the distance from a gravity supply is too great or the character of the country such as to make the building of canals impracticable.

The general principles involved in pumping for irrigation are not unlike those involved in pumping for municipal and domestic uses. Concerning the latter there are many data available which may have general application to pumping for irrigation. It must be recognized, however, that the quantity of water required for irrigation ordinarily greatly exceeds that needed for a municipal and domestic supply. Another important point to be considered is the value of water for irrigation purposes compared to what it is worth for the use of a town or city. A price which may be considered reasonable and which the residents of a town can well afford to pay for domestic use may be excessive when considered in connection with agricultural operations. This is because of the fact that the amount of water required for irrigation, considered with reference to cost, is excessive when compared with that necessary for all purposes in cities of moderate size.

The pumping equipment which would be well within the financial means of a city covering a thousand acres would be no more than adequate for a farm of the same extent. The return in revenue, however, between these two areas, one covered by business blocks and residences, is many times that which would be received from profits derived from the sale of crops grown on an equal extent of land.

Thus a pumping plant which might be of relatively low cost when considered for the city, is out of the question for the country.

The fundamental differences which must be considered in studying successful pumping plants installed for municipal purposes and in adopting similar plants for agricultural purposes lie in the following facts:

For city purposes a relatively small quantity of water is required to be lifted to a considerable height, in many cases 200 ft. or more, while for ordinary irrigation purposes 70 ft. is at present near the maximum. The quantity of water for city purposes is expressed in gallons per minute; that for agricultural purposes in cubic feet per second, 1 cu. ft. per second equaling 449 gal. per minute. The total quantity pumped is expressed for city purposes in millions of gallons; for agricultural purposes in acre-feet; 1 acre-foot equaling 325,850 gallons, or about a third of a million gallons; and one million gallons equaling 3.07 acre-feet.

The cost of raising water for a city may be as high as $20 to $30 per million gallons, or about $6 to $10 per acre-foot, while for ordinary field crops a fair cost would be 50 cents per acre-foot, and a large cost $1 per acre-foot.

For city purposes the supply must be practically continuous day and night, increasing during the extreme heat of the summer when water is used for irrigating lawns and gardens or similar small areas. Thus the men and machinery are kept continuously employed.

For agricultural purposes a supply is ordinarily required for a few months only during the irrigation season. Even during this period the amount required is by no means constant. For a short time during the early heat of summer the demand is large, but drops off rapidly as cooler weather approaches. Thus it happens that men and machinery employed in pumping for irrigation are idle for a large part of the time unless some secondary employment can be found for them.

Source of Supply.—A well of some form may be considered as the typical source of supply of water pumped for agriculture. Conditions may arise where it is possible to pump water from a flowing stream. As a rule such stream is of large size and has such gentle slopes that it cannot be diverted by gravity, otherwise pumps would not be used. Under some conditions water may be pumped from a lake or possibly from a canal. It is usually desirable, however, even in the case of a river or lake, to provide some form of forebay, which is practically a well built on the side of a stream or lake and connected with it so that the water in the well rises or falls with the fluctuations in the river or lake. Wells of this character, fluctuating within a narrow range, present fewer problems than the ordinary form of dug or driven well since the water in the former usually fluctuate less in height and thus offer fewer problems in the design cf economical machinery.

Having determined that the available source of water supply must be utilized by pumping, the next condition to be considered is the fluctuation in the height of water and the variation in amount, these being usually interrelated. If the source is a large stream or lake, the questions connected with quantity become insignificant and those of the amount of rise and fall of water surface are of more importance. In the case of ordinary wells in earth, however, the question of quantity or rate of delivery to the well become paramount, controlling as it does not only the height of water in the well, but the size and other conditions of the machinery to be used.

Observations of the height and fluctuation of the source of water carried on through several months or years are essential in preparing designs for a pumping plant. Every possible information as to the hydrographic conditions should be studied. If it is a matter of general knowledge that the lake or river under consideration has fluctuated within a certain range for many years these questions may be considered as settled. In the case of ordinary dug or drilled wells, however, the question of quantity of water is far more difficult of solution. Frequently it is impossible to give such wells a thorough test in advance because the cost of erecting testing devices—consisting of machinery of sufficient capacity to thoroughly exhaust the wells—may be practically as expensive as to build the final plant. The only tests which have real value are those which are made through days, weeks or months to determine as thoroughly as possible all local conditions of rate of flow to the well, for this purpose drawing down the stored water accumulated in the strata in the immediate vicinity.

There are many popular fallacies concerning the amount of water under ground, especially as regards the "inexhaustible" supply. The use of the word "inexhaustible" in this connection usually implies that with the ordinary hand pump or similar devices it has not been possible to appreciably lower the surface of the ground water. Another term which has come into general use in the west, especially in the region of the Great Plains, and which conveys erroneous impressions, is the word "underflow." There is, it is true, an underflow but the rate of this is exceedingly slow, and a more descriptive term would be "percolation." The word "flow" in the minds of most people is connected with the behavior of a river moving at a rate perceptible to the eye, such as a mile or two an hour. The "underflow," if it can be said to flow at all, moves at the rate of from 1 to 5 ft. a day, or possibly at a slightly more rapid rate when in coarse sand or gravel. The assumption occasionally made in popular literature that there is under ground a great river moving steadily forward and carrying more water than there is in sight on the surface is a fanciful rather than an actual condition. In western Kansas, for example, it is popularly stated that the Arkansas River carries more water underground out of sight than in the visible surface channel. A little reflection will show that this cannot be true.

Careful tests have been made to show the existence of this underflow and to secure measurements of the rate and direction of movement. This is done by putting down a series of wells in lines or groups and impregnating the waters of one of these wells with ordinary table salt or some other soluble material, the presence of which can be detected by electric or mechanical devices. It has been discovered that there is a definite forward movement of the waters percolating through the sands and gravels which underlie the Valley of the Arkansas River, and that the surface configuration does not necessarily indicate the size or extent of these deeper beds in which water is progressing southerly or southeasterly in a diagonal line across the present river channel.

These beds of pervious material are very large and their cross-sectional area is probably many times greater than the cross-section of the surface stream, but the extremely slow rate of movement of a few feet a day as compared with 2 or 3 ft. per second on the surface, results in there being a relatively small amount of water per annum carried through these sand and gravel beds.

There is little doubt that the ground water is reinforced to a certain extent by this slow, gradual percolation, especially through widely spread sands and gravels, but this rate of flow is rarely sufficient to maintain the water table at the original height in any country where wells have been in use to a notable extent. McGee[1] has pointed out that in all settled parts of the United States there has been a decided lowering of the water table, especially where the ordinary dug wells have been supplemented by a large number of the cheaper and deeper drilled or driven wells. He has also shown that in spite of wet years the water table does not return permanently to its former height. If this is true for regions where the demand for water from underground is limited chiefly to domestic supply or for the watering of cattle, the effect must be more marked where considerable numbers of wells are provided for irrigation of the surface, as the amount

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[1] Wells and Subsoil Waters, by W. S. McGee, U. S. Dept. Agriculture, Bureau of Soils, Bulletin No. 92.

of water pumped from these for agriculture greatly exceeds that which is needed for domestic purposes.

In constructing a well where the ground waters are apparently abundant, it is desirable to sink a caisson from the surface into the water plane as far as it can be driven, using a pump having a capacity twice that of the pump finally installed. When this is done, it is usual to drill in the bottom of this caisson two or more of the so-called California wells and connect suction pipes to the pump extending down into these driven wells. Normally these pumps will draw water from the wells and from the bottom of the caisson in which they terminate. If the water plane is drawn down it will then be possible to secure water from the wells even if the bottom of the caisson becomes dry. If the pump loses its suction from any cause the water plane will rise until the pump is submerged and again put in operation. As an alternative method, but one which is not usually to be recommended, is that of driving small tunnels to connect wells situated outside the caisson. A well made by sinking a caisson to some distance below the surface of the underground waters, and having its depth still further increased by drilled wells in the bottom of the caisson, is considered the most permanent form of construction that can be adopted.

Character of Pumps.—The pumps first used in irrigation were naturally those which previously had been found successful for pumping town supplies, namely, those with plungers or pistons. They fall into two classes—first, those placed horizontally with suction lift and requiring a certain amount of horizontal space for installation, and second, the vertical acting pumps usually so small in horizontal diameter that they can be inserted directly into the well and are thus frequently submerged, attaining, as a rule, greater efficiency because of this condition. These pumps were all of the reciprocating type, not well suited for economically delivering large quantities of water such as are required in irrigation. They have for this reason been supplemented in modern practice by centrifugal pumps of the single-stage type for moderately low heads and the multiple-stage type for high heads.

A form of centrifugal pump largely used and operated by electrical power for irrigation is one in which the pump and motor driving it are mounted on the same vertical shaft, frequently they are arranged in such way that the pump and motor can be raised and lowered as a unit. It is not practicable to mount the motor immediately above the pump because the fluctuations of water in the well are usually so great that the motor would be in danger of being submerged and thus injured. It is necessary, therefore, that the vertical shaft be of sufficient length to permit submergence of the pump and at the same time keep the motor well above the water level. This is accomplished by providing a light, steel frame on the upper end of which is carried the motor, and on the lower end the pump, the connecting shaft being supported by the frame at intermediate points so that the whole device forms a stiff but relatively light unit, which can be hung or supported in a well and, if necessary, adjusted to different heights to suit the elevation of water in the well.

The pump frame may be of galvanized structural steel, or iron, or of wood, and be suspended from beams placed across the top of the casing of the well, the internal diameter of which should be ample to permit insertion of the discharge pipe and the raising and lowering of the pump as shown in Fig. 34.

The pump is usually placed at a depth of from 30 to 50 ft. below the surface of the ground and a discharge pipe is carried up vertically to the surface independent of the frame. The adjustment is made so as to submerge the pump in such a position that the water surface may rise 15 or 20 ft. or more above the pump and fall possibly 10 or 15 ft. below it.

The capacity of centrifugal pumps arranged for irrigation should be selected to suit the varying conditions of head and available water supply. In this manner a high degree of efficiency can be obtained under all conditions, with the simplest form of automatically operated constant-speed apparatus. The maximum head which is practicable for the ordinary single-stage centrifugal pump is about 60 ft. Multiple-stage pumps may be used for any head desired. A modified form of the multi-stage centrifugal pump known as the deepwell turbine pump may be assembled in two or more units of such dimensions that the pump with its discharge pipe and self-contained shaft can be installed in a driven well casing and driven by either a belt or motor.

Power for Pumping.—Nearly every kind of power from the strength of animals, probably the earliest form, to the most modern hydro-electrical systems of development and transmission, has been used for pumping water for irrigation. At the present day it is not necessary to consider the use of animal power, although in a few instances under pioneer conditions or for testing the supply, various forms of machinery operated by horses may be temporarily employed.

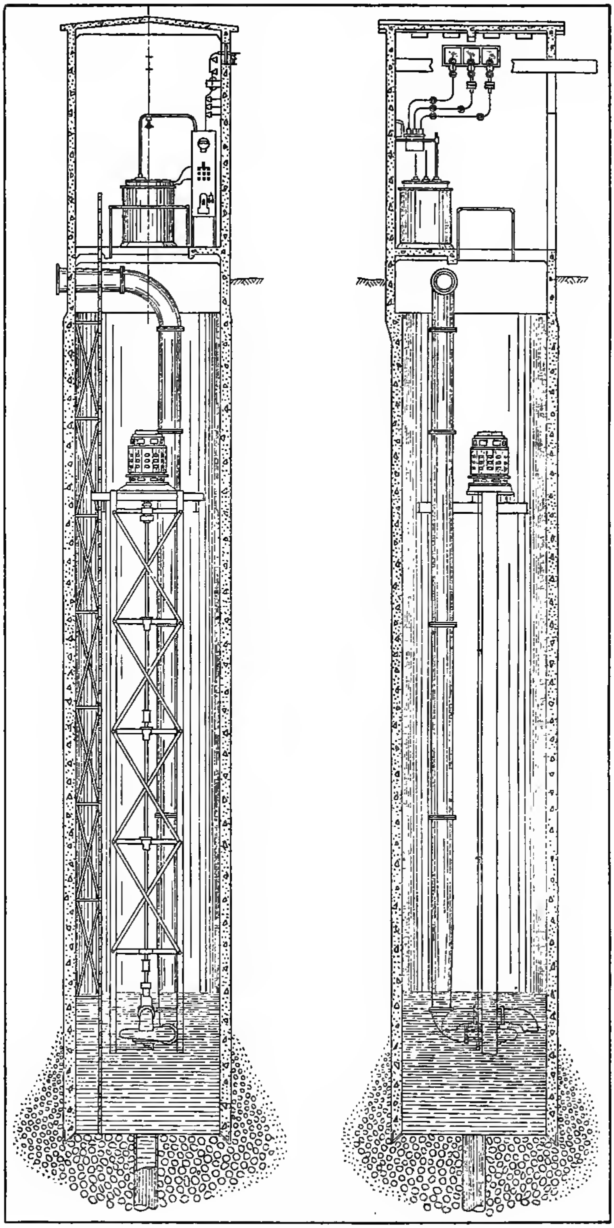

FIG. 34.—Vertical section of concrete lined well shaft, with electrically driven centrifugal pump, Salt River Project, Arizona.

Windmills.—Next in order historically, and naturally to the strength of men and animals, comes the use of wind. This is still quite largely employed for irrigating small tracts of ground. (See U. S. G. S. Water Supply Papers No. 1, 8, 20, 29, 41, and 42.) Windmills have been improved during recent years, adapted to various purposes and are now a commercial article readily obtainable through agricultural implement dealers. In considering the use of wind as a source of power, it is necessary mainly to secure a good commercial mill, using certain precautions, however, in estimating the actual available power, due allowance being made for assumptions based on ideal conditions.

It is usually necessary to supplement any form of wind-mill pump with adequate water storage because of the fact that the amount of water lifted is relatively very small, and with the uncertainty of the wind, this small stream of water coming at irregular intervals will soak into the ground before it can be beneficially used in irrigation. The necessity of a storage tank arises from the fact that in order to carry the water rapidly and effectively over the ground, it is necessary to have a considerable volume or head, such that the water will pass over or across porous soils so rapidly that no very considerable portion can be lost in transit. (See Plate IX, Figs. A and B.)

The cost of irrigation by windmills is generally prohibitory excepting for intensively cultivated market gardens. It is rarely possible to irrigate more than one-half or three-fourths of an acre with a windmill, unless the mill is unusually large, and the lift very low. The cost for irrigation including construction of well, purchase of windmill, pump, construction of tank, and accessories, may amount to from $100 to $500 an acre. The cost of maintenance is correspondingly large, as all forms of windmill require frequent attention and more or less repairs. The deterioration also is usually quite heavy so that the annual maintenance cost of the equipment rarely falls below $10 or $20 per acre, if allowance is made for the time spent in keeping the apparatus in order.

Steam Power.—One of the commonly applied forms of power for pumping is steam generated by burning coal or sometimes oil in the ordinary steam boilers, utilizing the force of the steam in reciprocating engines which drive suitable pumps by means of belt or gear connections or by direct piston connection. When used in irrigation the apparatus is sometimes an adaptation of the steam pumps used for town supply. Where the crops are very valuable, as in the case of sugar-cane in the Hawaiian Islands, steam pumps are used with success in agriculture, raising water 100 or more feet in height, the extreme limit being estimated at about 550 ft. The acreage cost for installation is, of course, exceedingly high, over $100 an acre at the minimum, and the annual maintenance and operation cost for high lifts may run from $30 to $50 per acre. The cost is thus prohibitory for ordinary crops, unless some unusual conditions exist.

Steam turbines have been employed in place of reciprocating engines, these being connected, as a rule, to electrical generators, which in turn operate motors to drive the pumps. A relatively high degree of efficiency has thus been secured and the size and consequent cost of installation has been notably reduced below that of the other devices. Especially is this true where a large quantity is to be pumped, and where several pumping units can be supplied with power from one central station.

Gasoline and Oil.—A steam plant for pumping water for irrigation necessitates, for fuel economy, large investment and the irrigation of considerable areas, more extensive usually than can be handled by an individual. There has thus arisen a demand for small individual pumping plants to irrigate from 40 to 80 acres, or more. For this purpose the ordinary gasoline or gas engines have been found very effective. Such engines may be considered as replacing or supplementing the windmill. They permit a control of the water supply such as cannot be had by dependence upon the wind and at the same time they can be of such size and capacity as to be within the reach of the individual farmer.

Pumping plants of this character have been installed at a first cost of from $50 to $100 per acre, and upward. The cost of operation and maintenance per acre is usually larger than that of the windmill and compares favorably with that of the steam engine but is higher than from gravity sources, ranging from $5 to $10 per acre. These forms of engines are undergoing rapid improvement and development, so that the engineer in considering the practicability of installing machinery of this kind should be advised of the most recent experience in order not to repeat the errors of his predecessors.

The gasoline engine using distillate is reported to be doing about 80 per cent. of that part of the pumping in southern California which is not being done by electric power—thus indicating a considerable advantage over the steam engine. These distillate engines use the cruder distillate from petroleum and are built up to as high as 300

PLATE IX

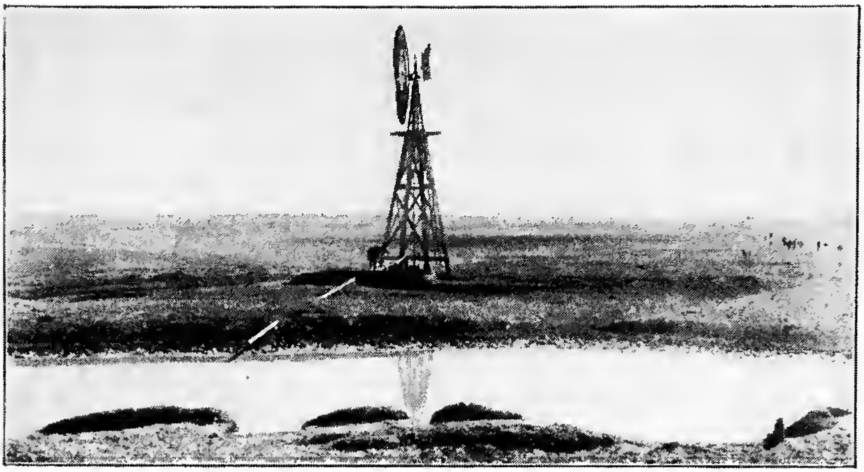

FIG. A.—Pumping water by wind mill into earth tank from which an irrigating stream can be drawn.

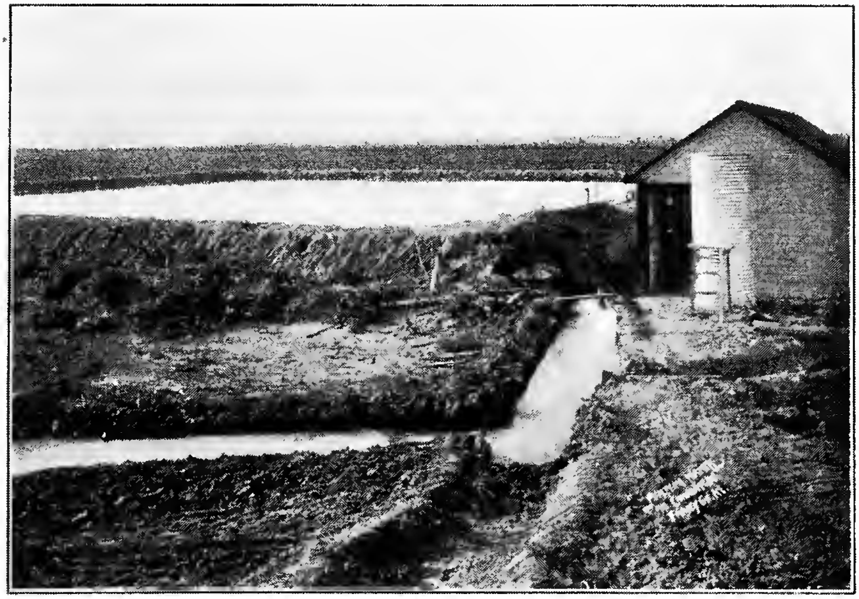

FIG. B.—Gasoline pumping equipment, delivering water into small earth reservoirs.

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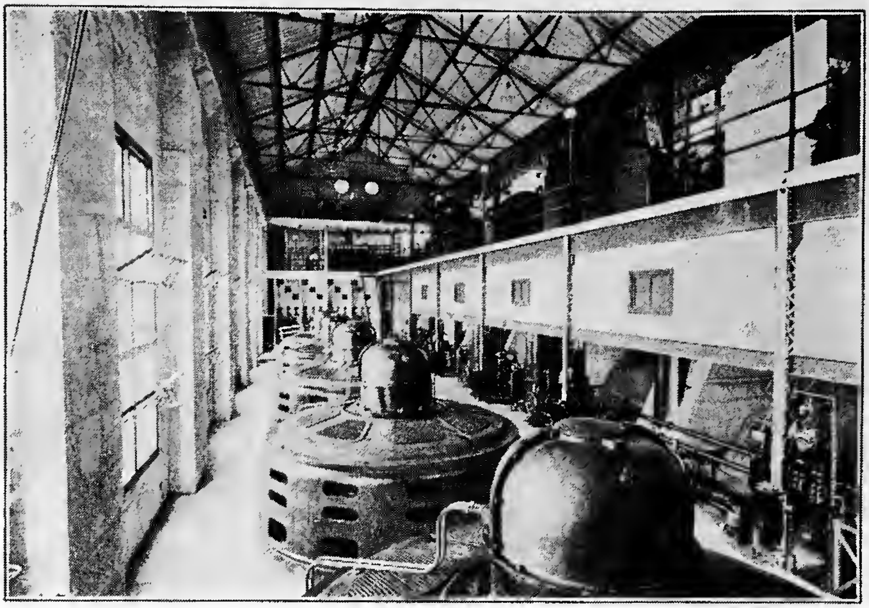

Fig. C.—Generators driven by water power furnishing electrical energy for pumps. Minidoka Project, Idaho.

Fig. D.—Electrically operated centrifugal pumps delivering water to laterals on Gila River Indian Reservation, Ariz.

h.p., thus irrigating large tracts of lands. Although the large distillate engine which requires the services of an engineer is not as economical as a high-grade steam plant using the cruder unrefined oils, yet as the irrigation of much of the country is subject to interruption, the lower first cost of the plant and the short time it is used offsets the higher fuel cost.

Many of the owners of orchards in southern California are supplying themselves and neighbors with water by engines which are not visited sometimes more than twice in a day's run of ten hours. The engines are reliable and fairly economical, if ordinary attention is given them. A still higher economy may be obtained when there are introduced various forms of producer gas from either oil or coal.

Water Power.—The use of water power is, theoretically at least, the most economical of methods for pumping water. Usually it is considered in connection with development of electricity and the transmission of power to points where the pumps are to be operated, forming thus a hydroelectric combination. There are cases, however, where it is advisable to install a water-power development at the point where the water is to be pumped. For example, on a main canal the topography of the ground may be such as to necessitate or make desirable the putting in of a drop in the bed of the canal. Power can be developed at this drop to lift a portion of the water to the lands above the level of the main canal. Automatic pumps for this purpose have been devised and successfully operated at relatively small expense, such for example in connection with the Huntley Montana Reclamation project, where, with the drop of 30 ft. in the main canal, a portion of the water is lifted to a height of 50 ft. above the canal to irrigate higher lands as shown in Fig. 35.

The device used at Huntley consists of a turbine wheel attached to the lower end of the vertical shaft on the upper end of which is a centrifugal pump, the water passing into the turbine wheel actuates it, driving the centrifugal pump which in turn is fed by a portion of the water which is flowing toward the turbine. This portion, about one-third of the capacity of the penstock, is forced upward to a higher level.

This machine is enclosed within a cylindrical case, so that all parts of the machinery are protected and when once installed the pump runs continuously with a minimum of attention throughout the irrigation season.

Hydraulic rams can also be installed in localities of this kind, this device depending upon the water hammer or ram of the water,

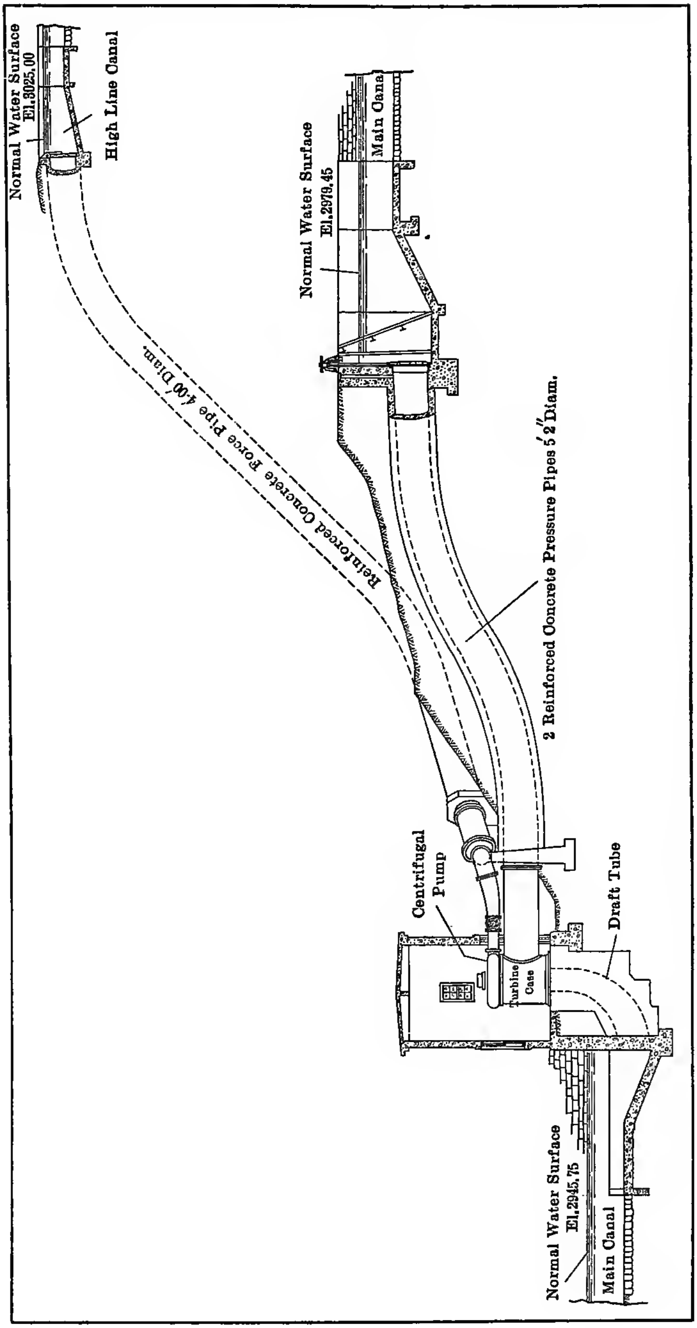

FIG. 35.—Section of pumping plant, on main canal, Huntley Project, Montana.

which when falling rapidly is suddenly checked, the momentum causing a portion of the water to be forced to a higher elevation. These rams have reached a capacity as high as 5 cu. ft. per second of delivery, and are found to be very economical for installation. They are very noisy and the shock of the arm rapidly wears the moving parts unless these are carefully adjusted. They are easily clogged or put out of order and on the whole have not given a high degree of efficiency for continuous operation for any considerable period of time.

Compressed Air.—Where compressed air can be readily obtained from an established plant, it has been found feasible to lift water from deep tubular wells by means of what is known as the air lift. For example, in the vicinity of sugar-beet factories or large mills where there is an excess of power or of compressed air, during certain parts of the year arrangements have been made for utilizing the air for lifting water for irrigation. The device consists essentially of an arrangement of vertical pipes by which compressed air is carried by means of a small pipe to near the bottom of the well casing, and there released. The air ascending through the water confined in the larger pipe forming the well tends to lift the water, causing it to overflow the top of the pipe. The advantages claimed are a large capacity, low maintenance cost, especially in sandy water which cuts the valves of mechanical pumps, and low operating cost, particularly where an air compressor is readily available. The disadvantages lie in the low efficiency, the relatively great depth required, as the air pump cannot be used in a shallow well or reservoir, and the impracticability of using highly inclined or horizontal course for the water.

The efficiencies as measured by various experimenters generally run from about 25 to 33 per cent., being higher in some laboratory experiments, but lower in actual practice. A comparison between the efficiency of wells pumped with air lift and deep steam pumps at Waukesha, Wisconsin, showed an efficiency of 16 to 18 per cent. for air lift based on the indicated horse-power in the steam cylinder, and an efficiency of nearly 75 per cent. for deep well pumps. (See Bulletin 450, University of Wisconsin, Oct., 1911.)

Hydroelectrical Power.—The use of power transmitted by electricity in pumping water for irrigation or the hydroelectric plant from an economic or engineering standpoint, is one of the ideal combinations of mechanical completeness and efficiency. Like most ideals, it is yet to be worked out completely, although the results already attained demonstrate the great possibilities. It occasionally happens that in planning an irrigation system, there is necessarily involved a drop of water from the point of storage back into the river or canal, or at some point along the main conduits.

Occasionally falls of water on the canal lines occur at points where direct pumping is not possible but where water-wheels may be installed, power developed and transmitted for the operation of pumps placed more conveniently to the irrigable lands. Under such conditions, the engineer should plan for the conservation of this power and prepare estimates as to the practicability of utilizing the power in bringing the water to the lands which otherwise could not be reached.

As an example of one of the recently developed hydroelectric plants built primarily for pumping water for irrigation is the station of the Minidoka project in southern Idaho, a plan and section of which are given in Fig. 36. A view of the interior of the power house is shown on Plate IX, Fig. C. This is located at the rock-fill dam across Snake River near Minidoka. This dam has a height of 86 ft. with length of rock-fill of 736 ft. and contains 242,500 cu. yd. of material. (See Plate XV, Fig. A.) It raises the water surface about 40 ft. forming a body of water known as Lake Walcott. A certain amount of water claimed by prior appropriators must pass through this dam for use at points below. In so doing power is developed for use in pumping water to the lands lying above the reach of gravity water from Lake Walcott.

The excess power, especially that obtained during the non-irrigating months is used for furnishing heat, light, and current to the towns on the project. Seven thousand kilowatts are generated in five separate units, and transmitted about 13 miles at 33,000 volts to three pumping stations. The first lifts about 650 cu. ft. per second to a height of 31 ft. above the gravity canal; at this level about 10,000 acres are irrigated. The balance of the water is pumped to an elevation of 31 ft. where another canal irrigates about 15,000 acres. The remainder of the water is pumped an additional 31 ft. to the highest level, from which about 23,000 acres are irrigated. The building shown in Fig. 36 is located on the down-stream side of the concrete controlling works across Snake River. The building is of reinforced concrete and consists of a turbine floor and generator floor and galleries as shown in Plate IX, Fig. C. The building is 150 ft. long, 50 ft. wide, and 85 ft. high on the down-stream side. The turbines when fully loaded are rated at 2,000 h.p., and used 425 second-feet of water under the normal head. The main electric units are 1,200-k.w. 2,300-volt, 3-phase, vertical alternators of the revolving field type, and are operated at 200 revolutions per minute.

In some localities, where it is not practicable to develop electrical power directly, it is possible to arrange for purchase of it from a source external to the project, and to obtain this at rates notably low, because of the fact that the power can be utilized in pumping at times of day or during seasons when there is least demand for it for use in other purposes, for example, in any large electrical power development for ordinary commercial purposes, provision is made for a certain maximum demand which usually occurs during the winter and within certain portions of each day. At times during each day, or after midnight and from then nearly to sundown there is an excess of power which may be had at small cost or at rates sufficiently low to justify pumping for irrigation.

There are several modifying conditions, however, which must be very carefully considered, the first of these is that of securing long time contracts or provisions such as will justify agriculture operations. It would be unwise to build a pumping plant for an orchard which will not come into bearing for several years, nor reach maturity for ten or twelve years, unless there is assurance that the power supply will be adequate and can be had at reasonable rates for a long period of years.

Where water-power can thus be had in connection with irrigation development, the engineer should give careful consideration to the economies which may result by extending the irrigable area to lands which, lying above the main canal, usually possess points of superiority either in soil, exposure or drainage. It frequently happens that excess water accumulates on the low lands, reducing the value of these. It is sometimes possible, under such conditions, to utilize cheap power transmitted by electrical devices in draining these lands, this waste water being used for the reclamation of additional areas. Where drainage waters are used for irrigation, attention must be given to their quality, as they frequently contain large quantities of harmful alkali salts in solution.

In considering hydroelectric developments of this character, the units commonly employed are the cubic foot per second for rate of flow and the horse-power or kilowatt (1. h.p. = 0.746 kw. or 1 kw. = 1.340 h.p.). Assuming the weight of water as 62.5 lb. per cubic foot, this amount falling 1 ft. per second develops 0.1136 h.p. = 0.0847 kw. Putting it another way, 1 cu. ft. per second falling 8.8 ft. generates

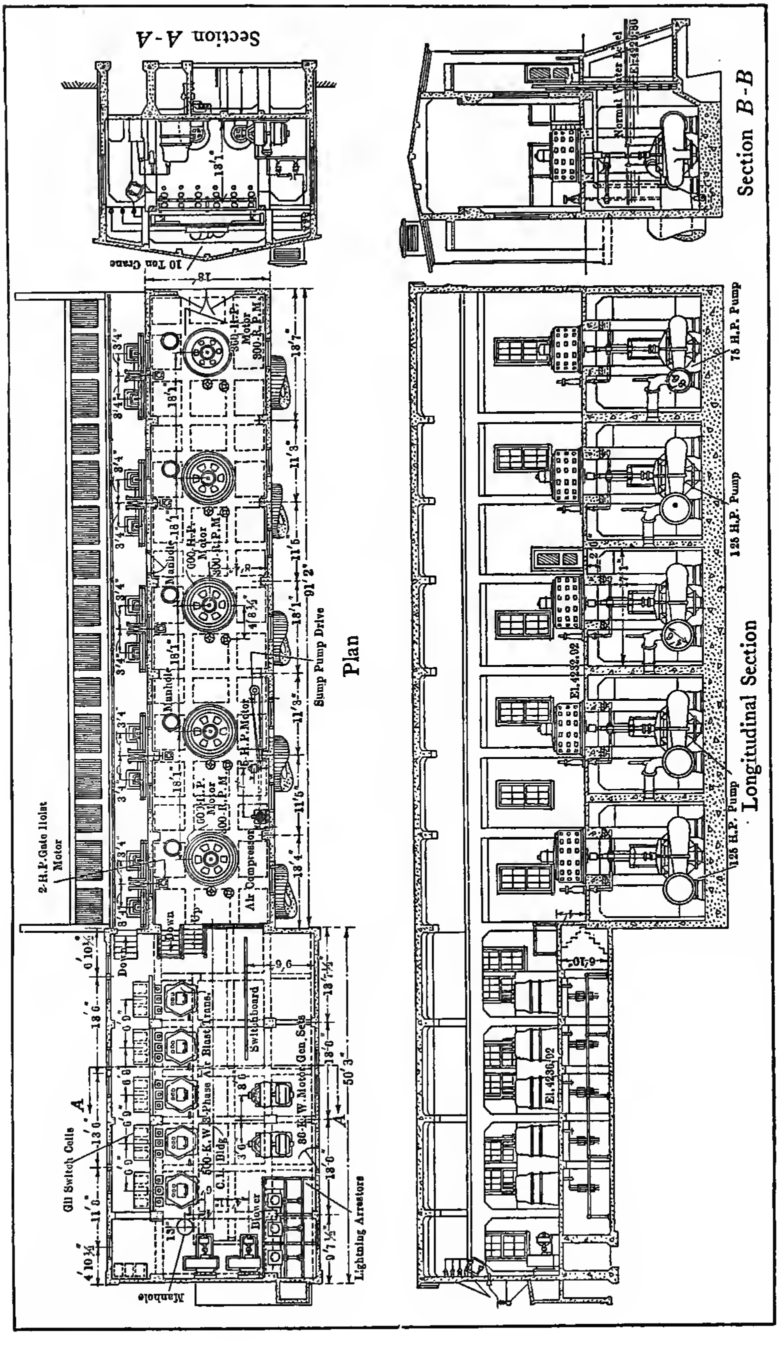

FIG. 36.—General plan and sections of pumping station, Minidoka Project, Idaho.

one theoretical horse-power, or 1 kw. per hour equals 1 acre-foot raised 1 ft. high. If for convenience in preliminary calculations a motor efficiency of 80 per cent. is assumed, 1 second-foot falling 11 ft. will generate 1 h.p. or 0.746 kw. (or 1 kw. = 1.340 h.p.). If the power is used for pumping water and the plant efficiency is taken at 50 per cent. for motor, pump, etc., then 1 acre-foot raised 1 ft. high will require at least 2 kw.-hours. By this simple rule the total power required to irrigate an acre may be apprehended by easy mental effort.

In estimating the energy created by falling water, it is convenient to make certain assumptions, as to the efficiency of the various forms of apparatus. The turbine water-wheel is assumed to have an efficiency under good conditions of 80 per cent. or over, some have reached in practice 87 per cent. or even 90 per cent. on tests. The generator may reach an efficiency of 90 to 95 per cent. From this it is customary to transform the power to a higher voltage for purposes of transmission and the transformer may be considered as having 96 to 98 per cent. net efficiency. There are certain losses in transmission line which may vary from 5 to 10 per cent., and it is fair to assume a transmission-line loss of this amount. Transforming the power again and reducing its voltage is another loss of 2 or 3 per cent. or more, so that the horse-power ultimately transmitted will be about as follows:

ASSUMED EFFICIENCIES

Turbines	80 per cent. net efficiency	80.0
Generator	93 per cent. net efficiency	74.4
Transformer	97 per cent. net efficiency	72.2
Transmission line	92 per cent. net efficiency	66.4
Transformer	97 per cent. net efficiency	64.4

Starting thus, with a theoretical 1,000 h.p. we arrive at the point of use with about 644 h.p. applied to the motors.

The cost of power installation varies widely with the amount of power developed, the character of machinery, and the surrounding conditions. For preliminary assumptions it may be considered as ranging from $45 to $80 per horse-power, depending upon the amount of hydraulic work necessary in the way of dams, power canals, etc. The cost of a pumping plant where large pumps are used may vary from $45 to $65 per horse-power, making the cost of a plant, ranging in capacity from 1,000 to 5,000 h.p., from $100 to

$175 per horse-power when completely installed, with transmission lines and other accessories.

The cost of operation also varies greatly with the character of the plant and the continuity of operation and amount of power used. It is for this reason impossible to give figures on the cost of operation which will be of value in any particular case. In pumping for irrigation the plant must lie idle a considerable part of the year, unless it can be used for other purposes, for example, as an auxiliary power for domestic or municipal supply. Under these conditions it may be possible to dispose of power at very low rates during the winter season sufficient to justify the operation of the plant in order to maintain the operating force and prevent increase of operating cost due to new organization each year.

In estimating the cost per unit of horse-power or kilowatt-hour, it is necessary to make certain assumptions concerning the load factor, that is to say, the ratio between the actual amount of power which can be developed continuously and the amount which is habitually being used. In other words, if under normal conditions machinery is capable of developing 100 h.p. but the average demand throughout the day is for only 75 h.p. the load factor may be considered as 75. During the day at short intervals there may be an overload and the electrical machinery is usually built to carry for brief intervals an overload of 50 per cent. or more. Again the load may drop down to a very small fraction of the total capacity of the plant, so that the average throughout the day under general conditions rarely approaches 100 per cent.

In estimating the economy of installation of a power plant, it is essential to consider the probable cost of this in comparison with the possibility of purchasing power, especially where it may be obtained at irregular intervals, when not needed for other purposes, and at correspondingly low prices.

Assuming that electric power can be purchased for pumping at 1 cent per kilowatt-hour at the switchboard, and that the pumps will be operated for six months in the year of 180 days continuously, with a load factor of 75, the cost per 100 kw. for the season will be $3,240.

The equivalent of this is 134 h.p. and this amount will raise 23+ second-feet of water to a height of 50 ft. serving for the irrigation, assuming an average duty of water of about 2,300 acres, at a cost of $3,240, or less than $1.50 per acre for power.

Cost of Pumping.—This is expressed either in terms of quantity of water delivered at a certain point, such for example as $1 per acre-foot or 30 cents per million gallons, or more generally in the terms of acreage served, as $2.50 per acre per season—the latter involving an assumption as to the duty of water. In discussing the matter from an agricultural standpoint, it is advantageous to use the cost per acre for direct comparison with cost of irrigation by gravity systems, and with the value of crop obtained.

As a rule, the cost of pumping water is higher than that of obtaining it from gravity sources. The first, or construction cost, may possibly be less than that of a gravity system, but the annual expense for operation and maintenance, including depreciation, is considerably higher. The cost is roughly proportioned to the height to which the water is raised, so that the controlling factor is largely the difference in elevation between the source of water in the well, reservoir, or steam, and the point of delivery from which it reaches the irrigable land.

Where the values of crops are very great as is the case in some of the highly developed fruit sections and with sugar-cane in the Hawaiian Islands, water for irrigation may be pumped to a height of 500 ft. or more. With ordinary crops of the temperate zone the present economical lift is considered as being not far from 60 or 70 ft. Theoretically, it should be profitable to pump to greater heights than these, but practically, this has not yet been successfully done.

In some sections the annual charges for pumping water is not less than $25 per acre, as for example, in the foot-hill region near Pomona and Ontario and in Orange County, California. In other sections where more favorable conditions obtain, the charges probably do not exceed $5 per acre per annum. Under exceptional conditions they may be even less than this.

In Western Kansas the cost is stated to be not far from 7 cents per acre-foot of water raised one foot in height, or $3.50 per acre-foot raised to a height of 50 ft. These figures roughly indicate the present condition of development of the small pumping plants. They include operation and maintenance, depreciation and interest on investment, costs of 5 cents per acre-foot raised one foot are not unusual and with better economy the cost is stated to be as low as 3 cents or slightly less. These lower estimates are generally based not on long-continued actual practice but on short-time or laboratory tests. The general appearance of the pumping plant and reservcir is shown in Plate IX, Fig. B.

It is difficult to obtain actual costs of pumping because of the fact that many of the private plants have been operated in the interests of the promoters or persons selling land and at a nominal charge for the purpose of facilitating land sales. It is generally agreed that at a later date when the land is sold the works will be turned over to the land owners to be operated at their expense. The losses which may be encountered in cost of operation during the time when the plant is new and the lands are being placed on the market are more than made up by the additional prices received from the sale of lands. This fact is cited so that engineers may not be misled by the relatively low annual charges occasionally quoted for pumped water, these not necessarily representing the actual cost, which in some cases may be twice as great.

Feasibility of Pumping.—The practicability of pumping water for irrigation is governed primarily by natural conditions, such as place of occurrence of water, height of lift, distance to the irrigable land, and mechanical difficulties growing out of these, all being summed up in the statement of probable cost. There may be an ample supply of water, and relatively cheap power, but the lands to be covered may be widely scattered in small tracts requiring long pressure pipe or distributing system over ground too rough or undulating to render the work successful, or the distance to markets may be too great. It is necessary, therefore, in considering this matter of obtaining water to take into account, as in the case of gravity systems, the economic as well as the engineering features, such as the quality of the soil, the ease of irrigation, the climatic conditions and markets governing the value of crops, and to study these in connection with the more purely mechanical side.

As stated in the paragraphs regarding cost, it has not been found feasible as a rule to pump water for ordinary crops in the temperate zone to a height much greater than 70 ft., but there are conditions where small tracts of land of exceptional quality and accessible to markets will justify the building of a pumping plant for raising water beyond this height.

The feasibility of extending the agricultural area by pumping is governed by the comparison of total costs with returns. Of the total costs, the item of power is frequently the large and controlling one. It is apparent that while at present this cost must be kept at a relatively low amount, as time goes on, as the soil is subdued and rendered more productive, as the orchards reach maturity, and as population increases and markets are established, it will be possible to incur a larger and larger cost per acre and to utilize sources of power which at the present time are considered as being too expensive.

The growth of the country is accompanied by an improvement in mechanical appliances and in the feasibility of purchasing waste or excess power from various industrial processes. As before stated, the excess power from lighting or transmission plants may be purchased and used when not in demand for the primary purpose for which the machinery was installed. These considerations should be given due weight in all plans for developing irrigation by pumping, and before stating the limit to any proposed system, these ultimate sources of power should be carefully studied.

The maximum height of lift which may be considered in planning a pumping plant for irrigation has previously been given as ranging from a present maximum of over 500 ft. for the most valuable tropical plants, citrus fruits and intensive truck farming, down to 60 or 70 ft. for the ordinary crops of the temperate zone. The controlling factor of height of lift is not set by mechanical considerations, but in each case these enter into the designing of the plant after determination has been made of the limit of cost which may be incurred.

In southern California, in the vicinity of Los Angeles, water is being pumped as high as 75 ft. for the purpose of raising alfalfa, and as this is one of the crops which requires a large amount of water, it may be assumed that if this can be successfully grown by pumping water to this height, orchards and more valuable crops may be cultivated with water lifted still higher. Each year the area of alfalfa thus irrigated is being extended, indicating that the operations are financially successful.

CHAPTER VIII

DRAINAGE

Classification.—The subject of drainage may, in a general way, be subdivided into two classes; namely, surface drainage and underground drainage. These two classes are not entirely independent, since it would be impossible to carry on any form of surface drainage without producing a certain amount of underground drainage, and equally impossible to carry on underground drainage without also at certain times disposing of surface waters.

Surface drainage ordinarily applies to the removal from the surface of the ground waters which have fallen upon it in the form of rain or snow. Surface drains are usually comparatively shallow open drains of sufficient capacity to take care of storm floods and carry them away quickly and before they have time to soak to any considerable depth into the soil.

Underground drainage applies to the removal of ground waters, or those which are below the surface of the soil. These ground waters may be the result of rains or irrigation in the immediate vicinity, or they may be carried for some distance underground and finally come near the surface on the lower areas in the path of their flow. Underground drains may be either open or closed; they differ, however, from surface drains in that the supply reaches them not over the surface but through the lower soil or sub-soil.

Drainage problems in connection with irrigation usually require the use of underground drains since it is the excess of irrigation waters that have been put into the soils that have to be removed. As this work is intended to deal only with problems of irrigation, underground drainage will be the principal subject treated in this chapter.

Needs of Drainage.—One of the first requisites for the growth of crops is moisture. The soil must be kept sufficiently wet to supply to the roots of a plant the water which it requires for its existence and growth.

Soils are made up of minute particles very irregular in shape and size. These particles when loosely thrown together, as is the case in properly cultivated soils, leave spaces of irregular shape and dimensions between them. The size of the spaces depend upon the size and shape of the particles forming the soil and the closeness of the particles to each other. It thus follows that a closely packed soil of the same material will absorb and hold less water than one which is loosely broken up, for the reason that the volume of the spaces between the particles is less in the former than in the latter case.

Each individual particle comprising a soil, due to the law of attration of matter, is capable of holding on its surface a minutely thin film of water. The mutual attraction between the particle and this thin film is so great that all the water cannot be drained out of a soil by gravity; in fact, to remove all of the moisture which clings to the minute particles of a soil except by carefully heating and drying is a very difficult process.

When a soil contains no perceptible water adhering to its individual particles, it is said to be dry; when it contains only so much water as is held by the attraction of the particles and no more will drain away, it is said to be moist; when the spaces between the particles are completely filled with water, it is said to be saturated. If an excavation be made in soil which is moist only, no water will flow from the soil into the excavation. If the excavation be made in soil that is saturated, water will collect and in a short time stand at the same elevation as the top of the saturated soil. The surface of free water or the upper limit of saturation in a soil is commonly called the water plane.

Vegetation requires moisture, but with the exception of aquatic plants, will not grow in soils that are saturated with water. In order to grow crops in an arid or semi-arid region—where the natural rainfall is not sufficient to supply the necessary moistures to the soils—this lack of water must be supplied by irrigation. Important as the supplying of water to land may be, it is equally important that any excess water which would cause the soil to become saturated be removed. Theoretically it may seem possible to apply to soils only the exact amount of water required for the growing of crops. Practically it is found that in nearly every case there is a certain amount of excess water which must be disposed of. When the soil is open or porous to a sufficient depth to permit the excess waters being carried away, natural drainage may be said to exist. Where nature has not provided natural underground drainage, it must be supplied artificially.

The fundamental problem in drainage is to control the elevation of the water plane and keep it below the zone of soil required for the roots of growing plants. If this is not done the roots cannot penetrate to the required depth to obtain the necessary nourishment from the soil.

In soils which contain harmful alkali salts, it is necessary also that the water plane be kept down in order to prevent on accumulation of these salts on the surface.

Alkali and its Effect.—As heretofore stated the soils of the arid and semi-arid regions are largely the results of disintegration of rock. Many of them have not been completely washed by copious rains during their formation and contain large quantities of soluble mineral salts. Some of these salts, especially in limited quantities, are beneficial and necessary for the growth of vegetation, while others are harmful, and in sufficient quantities will prohibit its growth. Sodium carbonate, commonly known as black alkali, is the most detrimental of all the alkali salts to plant growth. The exact action of alkali on a plant is not clearly understood, its effects, however, is to destroy the root tissues near the surface of the soil and leave the plant to die for lack of food and moisture. On account of the action of alkali being near the surface it is essential that any accumulation of salts in the top stratum of soil be avoided. (See Plate X, Fig. A.)

In their natural state the alkali salts are distributed more or less uniformly through the soils, frequently extending to considerable depths. When water is applied to the land, the soluble salts are dissolved. As the process of evaporation goes on from the surface of the soil and waters charged with alkali are brought up by capillary action there is a gradual accumulation of salts on or near the surface until finally the soil is unfit for the growing of crops. If the soil becomes saturated or, in other words, if the water plane is brought near to the surface, the capillary action in drawing water to the surface and consequently the rate of evaporation and deposit of alkali is increased.

Benefit of Drainage.—Reference has already been made to the necessity of artificial drainage on certain classes of soils to prevent their becoming unfit for use through the rise of the water plane and the accumulation on the surface of harmful alkali salts. On certain other classes of soils crops can be grown without drainage, but the soils are greatly improved and the value of the crop yield increased by its use. In such cases drainage may be classed as a benefit rather than a necessity. In this respect it may be compared to any

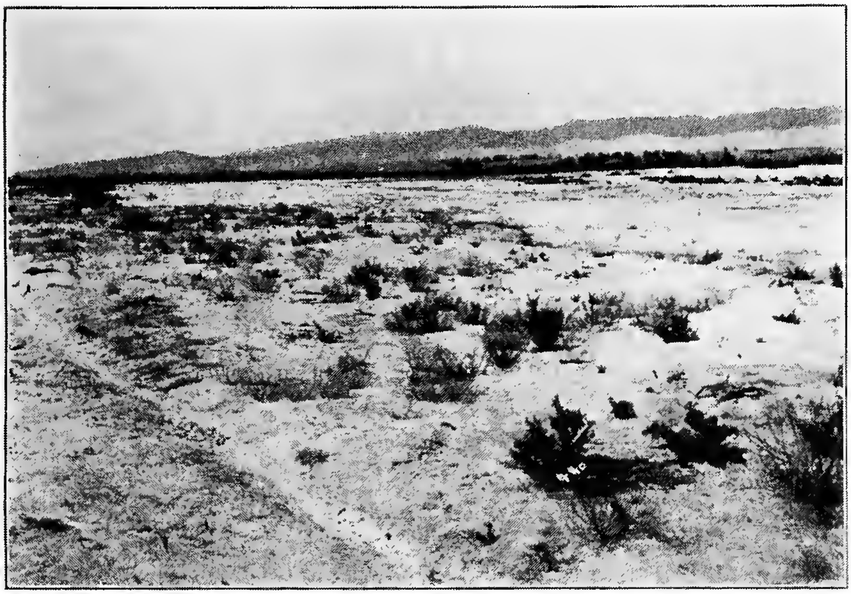

FIG. A.—Alkali flat, formerly a valuable farm, now ruined by careless irrigation and lack of drainage.

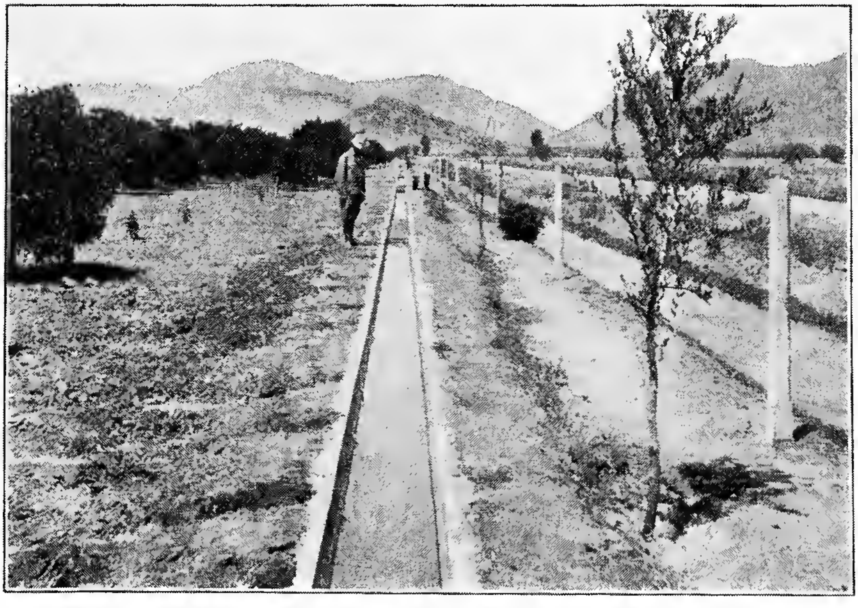

FIG. B.—Distributory lined with concrete to reduce loss of water and prevent development of alkali.

PLATE X

FIG. C.—Weir and self-registering gage. Williston Project, No. Dak.

FIG. D.—Automatic gage for recording height of water in river or main canal. Laramie River, Colo.

other method of improving the soil or increasing the amount of crop that can be grown. For example, on many soils crops will grow without the use of fertilizer, but it has been found that by its use the value of the crop may be increased by many times the cost of the fertilizer applied to the land.

Soils that are especially benefited by drainage are those which on account of their compactness do not allow a free movement of water through them. Soils must contain, in addition to moisture, a certain amount of air, in order that they be in proper condition to grow crops. It is necessary also that they be sufficiently loose and porous to allow the plant roots to penetrate them freely. It is possible for a soil to become so firmly compacted that there are practically no spaces between its particles and consequently it is impossible for either air or water to enter freely. Soil in this condition is commonly designated as water-logged, although the amount of water it contains is small on account of the lack of spaces between the particles to take up and hold moisture. A water-logged soil is cold due to the lack of the circulation of air through it. For this reason crops cannot be started as early in the spring on a water-logged soil as on a loose and porous one.

By providing for the removal of water from the lower strata of a water-logged soil by means of drainage and at the same time breaking up the surface by deep plowing or sub-soiling, the pores of the soil may be opened and a downward movement of water started. Air will be drawn into the soil, following the movement of water through it and in this manner the soil will be warmed and brought to the proper condition for growing crops.

Another important advantage of getting a downward motion of water started and air drawn into the soil by drainage is the removal of impure or objectionable vegetable matter. The roots of vegetation, it appears from recent agricultural investigations, leave in the soil a certain amount of organic matter, a portion of which is detrimental to some kinds of plant growth. The aeration of the soil carries into it the necessary elements for reducing the organic matter left in the soil by vegetation to a state that is less harmful to the growth of crops.

Summarizing, drainage may be said to be a protection against injury to land by raising the water plane too near the surface, and the bringing to the top soil, through capillary action and evaporation, harmful alkali salts. It is also an insurance of larger and better crop yields by keeping the pores of the soil open, thus permitting it to be warmed and purified through aeration, and kept in proper condition. It will also be shown later that drainage is beneficial in reducing the amount of water which must be applied to the soil in the process of irrigation.

Ground Water.—The term ground water as here used applies ordinarily to water below the surface of the soil. The upper limit of ground water is the top of the zone of saturation in the soil or what has already been defined as the water plane. In some special instances the water plane may rise until it is above the ground surface, as for example in low depressions. The elevation of the ground water in such cases will be regulated and controlled by sub-surface waters in the higher adjacent areas. Water which has been brought to or above the surface by the rise of the water plane and the elevation of which is controlled by an underground movement of water may properly be classed as ground waters.

The depths of ground water varies greatly in different formations, and in a comparatively small area, say of 1 or 2 square miles, may range anywhere from 1 to 100 ft. or more. It depends largely upon the depth to impervious material,[1] such for example, as a strata of clay or rock. It also depends upon the rate at which water will move through the pervious top strata, and the quantity of water which reaches the area, either in the form of rain or as applied for irrigation.

If a sub-soil is porous, the excess water which finds its way into it will gradually pass downward until it reaches an impervious stratum which prevents further downward motion. When the surface of the impervious stratum is level or inclined downward, the water will move laterally over it until it finally finds its way to some natural outlet and is carried away. In this manner the water plane, if the supply which reaches the surface is not too great, may be kept down through natural process. If the surface of the impervious stratum is irregular consisting, as is frequently the case, of depressions and ridges, the lateral movement is prevented and the water plane will rise until an outlet is found over the crest or through gaps in the impervious barriers. It thus follows that even with a

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[1] *Note.*—Materials which are absolutely impervious to water are seldom found in nature. For want of a better term impervious material is used in this chapter to designate material which is tight enough to prevent the passage of but a very limited quantity of water through it, such for example as firm clay or rock in place.

There is no sharp line of demarcation between pervious and impervious materials as found in nature; both are therefore to be considered as relative terms only.

seemingly porous sub-soil of considerable depth the water plane may be held up near the surface by the existence of impervious underground ridges or dikes.

When the amount of water which reaches a sub-soil is greater than can be carried away laterally over the impervious stratum, even though its surface be level, the sub-soil will become saturated and the water plane rise until it reaches the surface or until equilibrium of inflow and outflow is established. In the arid or semi-arid regions where irrigation has not been practised, ground waters are usually found at a considerable distance below the surface; this is on account of the limited rainfall and correspondingly small amount of water which reaches the sub-soils.

The rate of lateral movement of ground waters depends upon the porosity of the material and also the grade or slope of the water plane. A compact formation resists the flow of water first on account of the total cross-sectional areas of the openings through it being small, and second, on account of the minute size of each of these openings, since greater pressure is required to force water through them. On account of the complex nature of this subject, it is impossible to apply any theory to determine the porosity of a soil, in so far as it will affect the passage of water. Even in the most porous soils such as sand or gravel, the rate of water movement is very slow amounting to only a few feet per day, while in the most compact clays it is scarcely perceptible.

The elevation of the water plane relative to the surface of the soil is frequently affected by the varying thickness of a more or less porous stratum through which ground waters are moving. This condition is illustrated by considering a shallow sub-stratum of sand or gravel underlain by a stratum of imprevious material and also capped by a soil of clay or other semi-imprevious soil. The ground waters will move through the stratum of sand or gravel as this offers the least resistance to flow. If the thickness of this porous stratum is uniform or nearly so the movement of the waters will be uniform and but little if any upward pressure will be exerted against the less pervious top stratum.

At those places where the thickness of the sand or gravel stratum is diminished, due to thinning of the beds or the presence of impervious dikes or barriers projecting upward into it, the flow will be checked and the ground water will be put under slight pressure which will tend to force it to the surface. Examples are frequent in the irrigated portions of the arid west where waters have traveled underground for long distances and are finally forced to the surface on account of the porous sub-soil being obstructed or pinched out. Conditions of this kind are more likely to occur on or near the foot of slopes but are also frequently found on nearly level or uniformly sloping land.

Information relative to ground waters on a particular area can be obtained by means of borings put down to sufficient depths to show the elevation of the water plane and the character of the soil and sub-soil materials over that area. It is ordinarily possible from a study of these data to find the direction of movement of ground water and to determine the cause of the rise of the water plane too near the surface. In many cases the source of the ground water can also be ascertained; this, however, is not always possible on account of the long distance it sometimes travels before coming to the surface. It is impossible on account of the many unknown factors involved to form accurate conclusions relative to the movement of ground waters from surface indications or from theoretical considerations.

Effects of Drainage on Soils.—Reference has already been made to the benefits to be derived from drainage. The effects of drainage on soils which serve as a benefit may be enumerated as follows:

1. Removal of excess water.
2. Breaking up less pervious materials and increasing porosity.
3. Washing out impurities.
4. Increasing the capacity for retaining water.

The most important of these is the removal of excess waters from the soil. Most useful plants cannot survive in a soil saturated with water. The first consideration in drainage is to draw down the water plane below the depth to which the roots must penetrate. By keeping the water plane well down the roots are encouraged to go deeper for water. The result is a more hardy plant than could be grown if it were required to obtain its entire nourishment from a thin layer of soil near the surface.

The breaking up and rendering the soil more porous is accomplished by the downward motion of the water through it. This breaking up of the soil is also accomplished to a certain degree by the roots of plants penetrating it. Nitrogen is also carried into the soil by the roots of certain plants and the soil is thereby enriched. The downward motion of the water and plant growth work together in a well-drained soil to disintegrate it, rendering a thicker stratum available for plant food.

Impurities existing in the soil since its formation, as well as those which accumulate, are washed out by the downward motion of water. The soil is thereby kept in healthful condition so that plants can thrive in it.

One of the greatest benefits of the breaking up of a soil and rendering it more porous is its increased capacity for retaining moisture. In a loose soil the particles are sufficiently separated from each other so that when water is applied each particle holds a minute film of moisture clinging to its surface. The water thus held cannot be drained away and evaporation takes place slowly. The result is that moisture will be retained available for the use of plants much longer in a porous than in a non-porous soil. On account of the greater amount of moisture held by the particles there is less waste of water also. Moisture is consequently held in suspension which otherwise in a compact soil would be wasted over the surface or would have passed off laterally through the surface layers. It follows from this that the total amount of water which must be applied for the growing of a crop may if properly applied be less in a porous than a non-porous soil. Well drained land, strange as it may appear, requires less water to irrigate it than that which is undrained.

Open and Closed Drains.—The relative merits of open and closed drains are questions largely of economy in construction and operation. The action of a drain of given depth and capacity in drawing waters laterally to it and lowering the water plane is, so far as known, the same whether it be open or closed. This is assuming that each is kept in proper condition to take up the excess waters from the soil and carry them away. It is claimed by some that open drains under certain conditions become silted along the bottom and for some distance up the side slopes so that water cannot enter them freely. Examples have been found where the ground water immediately adjacent an open drain stood above the water surface in the drain; this, however, was due to an upward pressure against a relatively impervious top soil. The drains where this condition existed were not cut deep enough to intercept the pervious stratum below.

In considering the relative cost of construction of open and closed drains there must be taken into account in the former the value of the lands which they occupy in addition to the cost of building the drains. Open drains are a detriment to agricultural operations on account of cutting up the lands, and the opportunity which they offer for the growth of noxious weeds and grasses. The maintenance of open drains intending to regulate and control the elevation of ground waters is difficult on account of the tendency to become partly filled with weeds or other obstructions. When this occurs the effective depth of the drain is decreased, and its efficiency for drawing down the water plane is lessened. Open drains have an advantage over closed drains in that their capacity is not limited to a pipe or conduit of fixed dimensions, but increases as the water plane in the soil adjacent to the canal rises.

On steep slopes it may be necessary to construct drops in open drains in order to prevent erosion; in closed drains this is ordinarily unnecessary, the increased grade being an advantage in increasing the velocity of flow and reducing the size of drain required.

Closed drains permit all the land over which they are constructed being used, and obviate the objectional cutting of the land by open channels. When properly constructed they require little or no maintenance and are always in a condition to perform the function for which they are intended. In determining the question whether an open or closed drain is to be used in any particular case, the advantages of each from the relative cost of construction and maintenance and the probable efficiency for the purpose intended should be considered.

In general, it may be said that the closed forms are cheaper and better adapted for small drains intended to remove excess waters from the soil and hold down the water plane. Open trenches are ordinarily cheaper for the larger trunk drains where a considerable capacity is required.

The materials from which closed drains should be constructed will depend to a certain extent upon what is available in the particular locality where used. Clay and cement tiling, sewer pipe and wooden boxes have all been successfully used. The choice of one of these is largely a question of first cost and permanency of construction. Hard-burned clay tiles of good quality, so far as known, are not affected by any of the various constituents found in the soils and when placed deep enough to protect them from frost and surface cultivation may be considered as being as permanent as ordinary masonry construction. Cement tiling may also be considered permanent in soils which do not contain alkali. In some of the soils of the west, however, cement has been found to be disintegrated by the action of alkali upon it. Cement tiling for this reason cannot be recommended for use in lands containing alkali to any appreciable degree.

Vitrified sewer pipe with bell joints does not possess any advantages over hard-burned clay tiling with straight joints. It costs more than the ordinary tiling, and is more difficult to put in place on account of cutting out for the flanges in the bottom of the trench. The flange joints are also more likely to become silted than ordinary straight joints. One example has been reported of a drainage line made from ordinary vitrified pipe where the joints became sealed by silting so that no water could enter it. Wood on account of its tendency to decay cannot be considered as suitable material for closed drains where permanency is required. The decay of wood in a drainage line is hastened by the fact that portions of the drain may be dry during a part of each year.

On account of the nature of the work being such that close inspection cannot be made of it from time to time and the difficulty in finding and repairing breaks in a closed drain, permanent construction should be used wherever possible.

Relief and Intercepting Drains.—Drains are sometimes classed as relief and intercepting depending upon the manner in which water reaches them. A relief drain is one which taps a wet area directly and permits the ground water to flow out from different directions into the drain. An intercepting drain is one intended to cut off an underground flow and carry away the water before it reaches an area where the formation is such that it will rise to the surface. Relief drains are adapted to lowering and keeping the ground water at a safe distance below the surface. They are for the most part constructed in the lower portion of an area to be drained in order to draw down the ground water to the lowest elevation possible. Intercepting drains, on the other hand, are constructed above the area which they are intended to benefit.

Relief drains are of value in loosening and increasing the porosity of the soil by producing a downward motion of water through it. Intercepting drains are, in general, of no value for this purpose since they do not as a rule perform the function of drawing down ground waters over any considerable area.

It is impossible to compare the relative merits of these two classes of drains, on account of the different functions which they perform. Where the drainage problem is to draw off excess waters from a large area and improve the character of the soil by lowering the water plane and inducing a downward motion of water through it, intercepting drains are not to be considered. Where it is necessary to remove ground waters which are known to be traveling at a comparatively shallow depth it can frequently be done by means of an intercepting drain constructed crosswise to the direction of the flow. In order that an intercepting drain may work effectively it is essential that its bottom be below the pervious stratum through which the ground water moves. Where this is not the case, the flow will continue through the pervious material both from the lower side of the drain and also under it. On account of this limitation, conditions are seldom found where it is feasible to entirely cut off a flow of ground water. Intercepting drains may frequently be used to advantage in cutting off the greater portion of the ground waters flowing down a slope, the amount of drainage required on the more level lands below being thus greatly reduced.

Drainage Investigations.—Before attempting to make plans for the drainage of a particular area as full information as possible relative to the character of the soil and position of the water plane should be obtained. In gathering facts relative to soil conditions it is essential to ascertain whether the soil is uniform in character to the depth that drainage works should be constructed, or whether it is distinctly stratified with layers of clay, sand or gravel; and if so, the porosity of the different strata. The necessity for this information lies in the fact that the movement of ground waters takes place more freely in some of these layers than in others. In planning drainage works it is necessary to take account of the different carrying capacities for water of the various strata of which the soil is composed. Where a somewhat heavy and impervious soil, such, for example, as clay or adobe is underlain by a strata of gravel through which water moves freely, it is of the utmost importance that the location of the gravel be known and that it be taken into consideration in planning works to remove the excess water.

In addition to information relative to the character of soil, it is necessary to carefully determine the elevation of water plane over the area to be drained. After determining these facts it is possible to show graphically, either by contours of water surface or by cross-sections, the elevation and slope of the ground waters, and from this arrive at the direction of movement and the most feasible location for drains. It is important also that, if possible, the source of ground waters be determined. This can ordinarily be done by a study of the elevation of water surface and the character of the soil through which the ground waters move.

The information required for designing a drainage system usually can be best obtained by means of borings at short distances apart over the proposed area. The frequency of these borings and the depth to which they should be carried will vary in different localities, due to local conditions. They should be carried down to a sufficient depth to show the elevation of the water plane and the character of soils for some distance below the depth it is necessary to drain. They should be made sufficiently near each other to enable the elevation of the ground waters and the character of the underground formation to be known at any particular point with a reasonable degree of accuracy.

The portraying of the water plane for drainage purposes is not unlike the mapping by means of contours, of the surface of the ground for other purposes; such, for example, as the planning of irrigation canals and laterals. It must be understood, however, that the work of determining the contours of a water plane is far less accurate than the ascertaining of surface contours. The same is also true of the determination of the elevation and thickness of a sub-soil of sand or gravel. It is essential, however, in planning drainage works that as accurate data as possible be had. The source of underground waters which rise sufficiently near the surface to interfere with agricultural operations is, in many cases, difficult to determine. By drawing a series of water contours or cross sectional profiles indicating thereon the elevation of water plane over a given area, it is ordinarily possible, however, to trace out the high-water areas and from these a general knowledge is had of the local conditions and the direction of percolation of the ground water.

Capacity of Drains.—In arriving at the capacity of a given drain, consideration must be given, first, to the area to be drained, and, second, to the amount of excess waters to be removed. In estimating the area to be drained by any given drains or system of drains, it is necessary to take into account not only the area upon which the drains are constructed but the total area of land whose underground waters are tributary to these drains. As before stated, ground waters frequently travel for long distances at a considerable depth and finally come to the surface on a comparatively small area below. In determining the capacity of drainage works for this small area, particular attention must be given to the quantity of water which reaches it from an external source. At best, information of this kind which can be collected is only a rough estimate, since the amount of water which flows away from an irrigated area in any particular direction cannot be accurately measured.

The amount of excess waters resulting from a given depth on the soil, either from natural rainfall, or irrigation, or both, is also a question fraught with many uncertainties. Various assumptions have been made as to the amount of water returned from irrigation. It is doubtful, however, if sufficient accurately planned observations have been made on this subject to warrant definite conclusions being based upon them. In general, it is believed that by careful supervision of the operation of applying water to lands, the underground waste should not exceed 25 per cent. of the total amount applied to the surface. If this assumption be correct, and the amount of water applied to a particular tract during a year is 2 acre-feet, it is sufficient to plan a drainage system to remove 1/2 acre-foot per acre, or, in other words, a depth of 6 in. over the entire surface.

Irrigation ordinarily takes place during the summer months only, say from about the 1st of May until the 1st of October, a period of five months. It is not necessary to make drainage works of sufficient capacity to remove all of the excess waters during the irrigation period, since the soil has a large storage capacity and drains will be in operation for all, or a greater part, of the year. It is believed where the period of irrigation extends over less than six months of the year that twice the length of irrigation season may be allowed for the period of operation of drains. That is to say, where irrigation is carried on for a period of five months, a period of ten months may be given for the drains to remove the excess waters. If it is required to remove the equivalent of a surface depth of 6 in. within this period, capacity must be provided in drainage ditches of 1 cu. ft. per second for each 1,200 acres. The above estimates of the amount of water to be removed as previously stated, are not based upon actual measurements but are believed to be conservative. It is to be understood that for similar soil conditions the greater the quantity of water used in irrigation the greater the capacity of drains required.

Depth of Drains.—The depth to which drains should be constructed depends, first, upon the character of the soil as regards water movement through it; second, upon the capillary action of the soil in drawing water to the surface; and, third, upon the depth below the surface that the water plane must be maintained. Where the soil is underlain by a stratum of pervious sand or gravel containing water under slight pressure, it is ordinarily necessary to construct drains deep enough to tap this sand or gravel stratum and relieve the pressure in order to prevent water being forced to the surface. Drainage under these conditions is not a question of putting down drains to a depth of water plane required, but rather a question of removing waters from below so as to prevent their being forced upward through the soil stratum to the surface. Conditions have been found where water has been forced up to a considerable height above the grade of surface drains excavated in a somewhat pervious soil.

In such cases the lateral movement of water to the drains is not sufficient to carry water to the drains as rapidly as it is forced upward into the soil. Where a pervious sub-soil condition does not exist and ground waters do not reach the area from an outside source, attention must be given to drawing off the excess waters applied to the surface only. When this is the case, it is necessary to decide to what maximum elevation the water plane must be kept. This must, in every case, be below the zone of plant growth. It is necessary also that it be low enough so that the capillary action will not carry water to the surface in sufficient quantities to cause it to become seeped or bogged.

The distance that water will rise by capillary action varies in different kinds of soil. It ordinarily ranges from about 1 1/2 to 3 1/2 ft. In general, it is believed on irrigated land, the minimum depth to water plane should not be less than 4 ft., while, for certain kinds of crops, a greater depth may be advisable. The holding of the water plane down in this manner allows the plant roots to penetrate deeper into the soil and produces a more vigorous plant than can be obtained when growth is confined to a shallow depth. The depth of drains required to maintain a depth of water plane of 4 ft. will depend upon the amount of water applied to the soil, the freedom of movement of water through the ground, and the distance between drains.

The above are all questions which must be determined for each particular case and it is consequently impossible to lay down any hard and fast rules relative to the depth of drains. In general, it is believed, however, that on irrigated lands, drains to be effective should have a minimum depth of not less than about 5 ft., while in a majority of cases a greater depth is required.

Distance between Drains.—The proper distance between drains in order that they may be effective and at the same time permit of the most economic construction is, in most cases, difficult to determine. It depends primarily upon the rate of water movement through the soil and also to some extent upon the depth of the drains and source of ground waters. Heavy surface soils underlain at a comparatively shallow depth by an impervious material require the most frequent drains. This is especially true if the waters to be removed come from excess irrigation or rainfall directly on the area. With conditions of this kind drains are sometimes required at intervals of from 50 to 100 ft. in order to keep the water plane down to the required depth.

Where there is a sub-stratum of pervious material at a reasonable distance below the surface so the drains can be cut into it they may be effective at long distances. Under conditions of this kind the effect of drains may extend from half a mile to a mile on either side of them. The actual distance that the water plane will be lowered will, of course, depend upon the depth of the drain.

A rough idea of the distance a drain will draw water can be had from an examination of the soil. Accurate information, however, can only be obtained by observation on the water movement and slope of the water plane. This can frequently be determined by a row of test wells at right angles to a natural drainage channel. Where topographic and other conditions will permit, it is sometimes advisable to construct short drains for the purpose of studying their effect before making final plans for complete drainage. Observations on the effect of main or trunk drains may also be used to determine the frequency of smaller drains that will be required.

Grades and Velocities of Flow in Drains.—The most important considerations in determining the grades of drains is to provide on the one hand, sufficient velocity to prevent the drains becoming clogged and, on the other, to avoid excessive velocities such as tend to erode the channels. The first consideration applies to both open and closed drains, while the latter applies more especially to open channels in earth since closed drains are ordinarily of materials that will withstand relatively high grades and velocities. When the grades of earthen ditches are too high there results a cutting of the bottom or sides of the channel which undermines the banks causing them to fall. There thus results an irregular and unsightly ditch where the growth of noxious weeds and plants is encouraged. There may also be a considerable waste of land along the sides of the ditch. If there are any sections of the ditch where the grades are relatively flat the materials eroded above will be deposited in these sections and make the problem of maintenance more difficult.

The limiting grades which may be allowed in drainage ditches like irrigation canals will vary with the amount of water carried and the character of the materials through which the drains are constructed. Special attention must be given to each particular case in order to determine the proper grade to be used.

Where it is necessary to reduce the grade in an open ditch to prevent scouring, some form of drop should be used. This may be either a vertical fall with a water cushion below or a short length of channel built on a steep grade and protected by means of suitable material to prevent erosion.

The question of grades and velocities in open drainage ditches does not differ greatly from these same questions when applied to irrigation canals. It must be borne in mind, however, that the capacity of a drainage ditch is ordinarily much less than that of an irrigation canal and that in the former depth rather than carrying capacity is the principal factor to be considered. On account of the small capacity of drainage ditches the amount of grade which they will withstand is ordinarily much greater than in irrigation canals. Drainage ditches are ordinarily excavated into firm materials which erode less freely than the artificial banks of irrigation canals. For this reason also the dangers of cutting in the former are less than in the latter.

CHAPTER IX

OPERATION AND MAINTENANCE

Distribution of Water.—The primary purpose of constructing, maintaining and operating a canal system is to provide water for irrigation. The ultimate test of the success of the system from an engineering, and ordinarily from a financial standpoint, depends upon whether the water can be supplied to the lands under it at the proper time when needed. This depends, first, upon the character of the design and construction, and second, upon the efficiency of operation and maintenance. Whatever the importance of properly designing and constructing irrigation works, the importance of properly maintaining and operating them is equally as great.

Operation and maintenance requires the determination of the best methods and policies to be pursued, and involves questions of an administrative and engineering nature. Both of these are complicated on account of the right of the farmer to receive water from the system at the exact time when needed. The delivery of water therefore must be given first consideration, and the methods to be followed in making deliveries, and in maintaining canals must be such as to permit operation being carried on continuously. To the farmer who is dependent upon an irrigation supply of water for his success and livelihood nothing but most extraordinary conditions are sufficient to justify the cutting off of this supply even for a single day at the time when it is required for the growing of crops.

There are a number of ways by which water for agricultural purposes is distributed to lands. These are to a limited extent the results of careful experiment and scientific investigations; and to a greater extent the outgrowth of the crude methods used by the first irrigators. The subject of best handling water for irrigation purposes is in a formative state, and much work remains to be done by engineers and irrigation managers to devise means best suited to each particular case. In order to improve present methods it is necessary to devise others better suited to conditions, and also to overcome the prejudice which commonly exists against changes in agricultural operations.

Generally speaking there are two quite distinct systems for the distribution of water to lands, viz., continuous flow and periodic rotation. In order to consider the relative merits of these two systems and results which may be expected from each, it is essential that there be taken into account the conditions of the soil necessary for the growing of crops, and also the effect of water continuously and periodically applied to it in producing these conditions.

Continuous Flow.—The distribution of water by the continuous flow systems assumes that a stream of water of sufficient quantity to supply the needs of a given area is kept constantly flowing upon it. Take for example a tract of say 50 acres, and let us assume that it is desired to deliver to it $\frac{1}{2}$ acre-foot per acre during a period of thirty days. The volume of flow required to deliver this quantity is $\frac{50 \times 0.5}{1.98 \times 30} = 0.42$ second-feet, an amount usually too small for economical handling. For a larger or smaller area a proportionately larger or smaller flow is required.

The distribution of water by continuous flow imitates natural brooks or creeks. It was the system naturally adopted in the early stages of irrigation development in the United States. The smaller streams were diverted from their channels and carried out in long lines of canals, which were divided and sub-divided, each carrying a small amount of water to its respective owner. These canals were diverted in meandering courses across the fields and when water was not required on the lands it was allowed to waste back into the stream. The amount of water which was delivered to a given area was not restricted to that which could be beneficially used and seldom was there an attempt made to conserve the water supply. When water was plentiful (as was the case during the flood season) the farmer used all he wanted without special attention being given to the amount which should be applied to the soil, and when water was scarce, it was regarded as a condition for which no one was to blame.

As irrigation developed, and the demands for water increased, it became the custom to limit the amount which each man might receive, this quantity being defined by a stream of given size. From the standpoint of the farmer who desires water continuously on his land so that irrigation can be carried on at any time, regardless of whether or not the soil is in proper condition for irrigation, such a system has its advantages. Also where water is considered as a commodity to be owned by an individual without reference to whether or not he can use all, or a part of it to advantage, a continuous flow system is well adapted to measuring to each individual that which he owns. The disadvantages of using this system for delivering water for irrigation, however, are many.

In order that the soil may be in proper condition for growing plants, it is necessary that it be kept supplied with moisture to the depth penetrated by the plant roots. It must not, however, be given sufficient water to become saturated. The only practical plan of obtaining this condition is to apply to the surface, at more or less regular intervals, a sufficient supply of water to moisten the soil to the required depth. The moisture thus applied is held in suspension by the soil particles until taken up in part by the plant roots and in part by evaporation from the surface. When the supply of moisture becomes exhausted so that the plants can no longer find sufficient to sustain them, another irrigation is required.

By the continuous flow system portions of the land over which the water flows become saturated, or too wet for plant growth to thrive upon it. This is due to the fact that the soil is not given an opportunity to free itself from the excess water which is applied to it. In addition to the injury of lands to which water is directly applied, injury to those adjacent thereto is frequently caused. The result, therefore, is ruinous to the lands of the irrigator using this system, and possibly also to those of his neighbor.

The quantity of water required for the irrigation of a small tract of land, as for example the ordinary farm, when delivered continuously produces a stream too small to permit its being properly distributed. This is especially true on farms the soil of which absorbs water rapidly.

In general it may be said that the continuous flow system of delivery is wasteful of water, detrimental to the soil and not well adapted to carrying on irrigation operations.

Periodic Rotation.—This method of delivering water, as the name implies, is to supply to the land at somewhat regular intervals the amount of water it requires to keep it in proper condition for plant growth. It differs from the continuous flow system previously described in that the smaller canals, especially those to individual water users, carry water during only a portion of the time. When water is required on a given area a sufficient quantity is diverted to cover it in the shortest possible time, and the supply is then passed on to the next irrigator.

The advantages of this method may be enumerated as follows:

1. It permits of more even distribution of water, since the lands adjacent to the smaller canals do not become saturated as is the case where water is flowing continuously in them.

2. The soil is kept in better condition by being allowed to become warmed and aerated during the period when water is not applied to it.

3. It permits of more economic irrigation, since the farmer receives his supply in sufficient quantity to permit its being carried quickly over the lands.

4. The system is economical in the use of water, due to the fact that unnecessary waste and losses from the smaller canals is avoided, and water is delivered only when and where it is needed.

The delivery of water by periodic rotation imitates on a small scale the efforts now being made to conserve the water supply of a given stream or watershed, so as to make it serve the largest possible area. To accomplish this the water is held in storage and diverted to the streams or canals only when actually required for irrigation.

The partial drying of the soil after one irrigation and before the next is applied permits greater freedom of cultivation, which serves to reduce the quantity of water required. Thorough cultivation, to a certain degree, can be made to supplement a deficiency in water supply, by reducing evaporation from the surface.

The period of rotation in any particular case will depend upon climatic conditions, character of soil, and kind of crops raised. The essential requirement is that water be applied to the soil at periodic intervals when required.

Length of Irrigation Season.—The actual time during the year that irrigation is required, or the irrigation season, as it is commonly called, varies greatly in different localities. It depends primarily on the climate in regard to temperature and seasonal rainfall.

In the regions where long cold winters prevail the irrigation season is necessarily limited to the late spring and summer months and no water should be placed upon the lands until they have been warmed sufficiently by the approach of summer to stimulate plant growth. In a climate having a more or less definite season of rainfall, during the spring or early summer irrigation is frequently not needed until the rainy season is passed.

Where the climate is sufficiently mild to allow crops to grow during the winter season, as is the case in some of the arid regions of the southwest, irrigation may be required throughout the entire year. Ordinarily, in this section the natural rainfall is too small or too erratic in character to take the place of a single irrigation.

During the irrigation or growing season water sufficient for the plants should be applied to the soils; as soon as the growing season is over it should be shut out of the canal system so that the soil may become dry and aerated. With the approach of spring it is then warmed and early planting may result. If irrigation is practised during the non-growing season the presence of the excess moisture in the soil renders it less porous and less responsive to the sun's action.

In the more northern and colder portions of the United States the irrigation season extends from about the 1st of May to the 1st of October. Going southward the season gradually lengthens until, as above stated, it is continuous throughout the year.

The proper time to begin irrigation in the spring and to discontinue delivering water in the fall are questions of importance in operation and maintenance work. It may happen that the benefits of late fall irrigation to one season's crop may be more than offset by the damage it does in retarding the first crop of the following year. No definite rule can be formulated as to when irrigation shall be begun or ended. A careful study of soil conditions and the results that may be accomplished is the only guide.

Frequency of Irrigation.—There is a wide variation in the time which may elapse between irrigations. It depends upon the climate, soil and character of crops raised. Coarse, porous soils, such for example as sands or gravels, hold but little moisture in suspension. In a climate where the rate of evaporation is high, the moisture near the surface is rapidly exhausted. Shallow plants on soils of this kind require irrigation at intervals of a few days. By some farmers it is held that root crops planted in porous soil require water at intervals of from one to two days. Experience has shown that that is excessive and that better results can be obtained with less frequent irrigation.

For alfalfa, the stable forage crop of the west, it is sufficient in the more northern localities to apply water once for each cutting. Further south in the warmer regions each crop is ordinarily irrigated twice or more, water being applied in some cases every ten days during the warmer months.

It is evident that for complete success the frequency of irrigation must be adapted to the character of crops, time of planting, etc. The schedule for supplying water to the fields in the district must be arranged with a full knowledge of the crops growing in that district. In other words, there must be complete coöperation and good business management between irrigation managers and farmers, acting individually or in groups. If one crop is of such a character or is so planted as to require irrigation during a certain week, the schedule for water deliveries must be arranged accordingly or the crop will suffer. If the crops are of such nature as to require daily application of water, some special provisions must be made for supplying them. In other words, it should be remembered that the primary purpose of irrigation is to supply crops with water, and no rules relative to times of delivery should be so iron-clad as to interfere with this purpose.

An example of one of the schedules actually used by the United States Reclamation for the operation of the Williston pumping plant, North Dakota, is as follows:

> "The operation of the Williston canal system for the season of 1911, will begin June 4. In order to secure economical and uniform operation, deliveries of water from the different canals will be restricted in so far as practicable to the dates listed below, water to be delivered in rotation, beginning at the lower end of the system, running continuously until irrigation is completed, and in such quantities as can be most advantageously handled.
>
> "Water will be delivered from:

Canals B & S, and Canal A, South of Station No. 2.	Canals D & E, and Canal A, North of Station No. 2.
June 4 to June 13	June 14 to June 23
June 24 to July 3	July 4 to July 13
July 14 to July 23	July 24 to August 2
August 3 to August 12	August 13 to August 22

> "Application cards, stating whether water is desired during a ten-day run, must be mailed and received at the project office two days prior to the beginning of each ten-day run, and the water-user will be notified in advance when delivery will commence. If it is not convenient to take water at the time designated, it will be necessary to wait approximately twenty days until the next ten-day run."

Duty of Water.—The term "duty of water" is a form of expression for the quantity of water required for irrigation. It is sometimes expressed as the area which a continuous flow of a given amount will irrigate. For example, it may be said that the duty of water is 1 second-foot for each 100 acres, meaning that 1 second-foot continuous flow will irrigate 100 acres. Another way of expressing duty of water is by means of the depth applied to the land, that is, the number of acre-feet per acre for a given period of time, for example, a month or a year. The larger the area irrigated by a given quantity the higher the duty of water is said to be.

The determination of the proper amount of water to be used in irrigation is perhaps the most difficult question to be solved by the farmer and irrigation manager. It is affected by the kind of crop, character of soil, the rate of evaporation in the particular locality and also the skill of the irrigator. When water is applied to the soil a part of it is taken up by the growing plants, a part is consumed by evaporation from the surface, and a varying amount is lost by being carried downward through the sub-soil and eventually returned as drainage water to the streams below.

It is estimated that to produce 1 lb. of dry vegetable matter requires from 300 to 500 lb. of water. Using this as a basis, it would require from about 2 1/2 to 4 1/2 in. in depth over the land to produce 1 ton of dry matter per acre. It is of course impracticable to apply the theoretically exact amount of water to the land on account of evaporation and other losses which cannot be measured.

It is ordinarily impossible to irrigate lands without some water being lost by its penetrating below the zone of the plant roots. Various estimates of the amount of such losses have been made, but on account of the varying conditions met with it is impossible to apply them with safety to any particular case. It is believed that the loss by percolation below the plant root zone should not exceed 25 per cent. of the total quantity placed on the land, and that under careful irrigation on average soils it may be made much less than this.

The determination of the proper amount of water to use, as a practical question, can best be solved by observations on the condition of the soil under varying water deliveries. In doing this care should be taken to see that more water is not applied at any one irrigation than the soil can absorb and hold in suspension.

Investigations made during the past few years seem to show that in most irrigated sections where the quantity of water is not limited, more is used than is necessary. The result of this excess use is a decrease rather than an increase in crop production. It also has the effect of impoverishing the land by leaching out valuable constituents or rendering them waterlogged or alkaline.

On the projects of the United States Reclamation Service the amount of water required for a season's irrigation varies according to the best data available from 1.5 to 3.5 acre-feet per acre, the average being about 2 acre-feet per acre.

In addition to the losses due to the application of too much water to the soil there are also frequently large losses in transportation. Water is carried for the most part not in tight pipes or impervious conduits, but in open ditches built through more or less porous soils, and distributed by furrows passing often through sand or gravel areas in which a small stream may completely disappear.

The quantity which must be delivered to canals is, thus, greatly in excess of the quantity theoretically needed on the land. To carry this amount to a point where needed, it is necessary to send it in considerable volume, or "head" so that it can flow quickly across the more porous places. The larger the head of water in a canal the greater the velocity and the smaller the percentage of loss due to seepage.

As seepage losses only occur from the wetted perimeter of a ditch or furrow, it is obvious that the quantity of water can be greatly increased in the canal without notably adding to this wetted perimeter and consequent loss; also, if the amount needed to irrigate a field can be applied in half the usual time, it is apparent that the losses from this source will be reduced. Quickness in applying water results in economy, and the quantity needed is dependent largely on the skill and rapidity of application of the water. This in turn is governed to a certain extent by the size and location of the canal and structures, slope of ground and character of soil.

Measurements of losses by seepage and evaporation indicate that these losses in some cases are very great and that one of the most important steps for securing economy in the use of water is in reducing these losses. As long as open canals are used there must be a steady loss through evaporation. The expense of reducing these losses by covering the canals or putting the water in closed pipes will probably be far in excess of the value of the water under present conditions, but the seepage losses from the sides and bottoms of the canals should be reduced wherever practicable, as these are frequently of injury, not merely in the loss of the water itself but in the seeping and rendering swampy or alkaline of lands even at considerable distance from the canals.

Measurements of losses have been made on various canals giving results of which the following are examples:

From the feed canal on the Umatilla project, Ore., the loss by seepage and evaporation in the season of 1909 was 13.2 per cent. of the amount taken into the canal, this begin equivalent to 396 acre-feet per mile of canal or 98 acre-feet per acre of wetted area of canal.

On the distributing system of the same project the losses by seepage and evaporation amounted to 41.4 per cent. of the amount taken from the reservoir.

On the Minidoka project, Idaho, the loss between the amount taken into the main canal and turned to the sub-laterals was on the north side gravity system 29 per cent. and on the south side 47 per cent.

On the North Platte project, Wyoming and Nebraska, the losses on the main canal were from 4 to 14 per cent. and on the laterals from 5 to 39 per cent., dependent on the character of soil traversed. The average elsewhere was about 18 per cent.

On the Truckee-Carson project, Nevada, the average losses on a portion of the distributing system were 20.7 per cent., and on the Okanogan project in Washington from the main canal and distributing system were 45 per cent.

An average series of measurements made on the Yakima project, Washington, in 1910, showed that of the total amount of water taken into the main canal and branches 22.4 per cent. was lost, of that taken into the lateral system 32 per cent. was lost, and of that taken into the sub-lateral system 15 per cent. was lost.

Measurement of Water Used.—Measurements of water used in agriculture are as essential to the proper conduct of a system of irrigation of any considerable size as are measurements of the supplies sold by a produce dealer. Without accurate measurements and records confusion and loss quickly result. In the case of a very small system, there is obviously not the same necessity for making measurements any more than there is of the individual householder carefully weighing out the supplies for current use. But where hundreds of individuals are concerned, and where apparently insignificant errors may accumulate in a large general loss, there common sense and business rules demand accuracy and system in management and in accounting.

In the accompanying Plate X, Figs. C and D, are shown measuring devices as used on some of the irrigation canals. At Fig. C is a weir and self-registering gage such as has been installed on the Williston project, North Dakota, where water is pumped from the Missouri River. Fig. D is a view of an automatic gage such as is used at one of the stations on the Laramie River in Colorado.

The amount of water held, or turned out of the reservoirs, or received at the head of a system, must be recorded from day to day. Following down the main trunk line, there should also be measurements at several points in order to check losses through seepage, and to verify the measurement at the head. As the water is turned out in each of the principal branches, it should again be measured so that for each district, or division of the canal system, the amount of water received each day should be known and losses again checked. Finally, the amount measured to each farm or group of farms, together with the time of delivery, must be recorded in order to have accurate data to settle the innumerable disputes which may arise.

The measurements of larger quantities of water discharged from a reservoir or received into the head of a canal are usually made by some form of weir or submerged orifice. Where the latter is used it is usually calibrated by means of a current meter. The width and depth of the stream is obtained by direct measurement and the velocity of all parts by any one of a considerable number of devices on the market, most of these consisting of a rotating wheel, the speed of which varies with the velocity of flow. All such instruments must be rated, that is, the ratio between the speed of the water and the number of turns of the wheel per second being determined by direct measurement for each instrument.

Wherever there is ample fall, it is preferable to make measurements by means of a weir, following the conventional forms, and using tables computed from formulæ based on experimental data giving the ratio of water flowing to a depth on the weir.

The measurement of these large volumes of water is relatively simple, and follows well-established practices. The greatest difficulties, however, are encountered in measuring economically the smaller quantity of water directly to the field of the farmer. There are a great many devices for this purpose, but those which yield fairly accurate results are quite expensive. The problem of introducing and using these on an old canal system is similar to that of attaching meters to the service pipes in a city. Theoretically this should always be done, but practically the cost of the instruments and care required has been a great obstacle. In the same way, the cost of procuring, installing, and maintaining a suitable measuring device or module at each farm has been so great as to be almost prohibitory for the ordinary irrigation system.

The devices used for measuring water to the farmers have usually been somewhat crude, being manufactured locally, and consisting of measuring boxes made of plank or boards, in which by adjusting small wooden, or iron gates, the water is allowed to escape through a rectangular orifice. Where there is sufficient head, it is sometimes allowed to flow over a small weir, and for each of these weirs a table is made to show the quantity of water discharged. Where it is not possible to provide a fall or drop in the water from the canal or lateral to the field, the water is sometimes conducted in a wooden flume on a nearly level grade, in which measurements are made of the width and depth, and the velocity ascertained by small floats, or by current meters devised for the purpose. In this latter case a table is prepared showing the quantity of water flowing for different depths in the flume.

Human Element.—In the practical working out of an irrigation system, and in the distribution of water to the land the most serious consideration is not the engineering or mechanical difficulties, but those which arise from having to deal with considerable numbers of men of more or less limited education, coming from all parts of the world, frequently with strong native prejudices, or with experience under conditions entirely different from those had under successful irrigation. Many of these men must unlearn much which they regard as of first importance. Others have none of the qualities which lead to success in farming. Some are of a roving disposition who are attracted by the novelty of a change in vocation or by the glowing advertisements of land speculators.

Under these conditions factions arise, and under even the most patient and tactful management there are always a number of farmers or settlers who attribute their lack of success not to themselves but to the operation and management of the irrigation works.

Since the salary paid to a superintendent or manager of a system is not always sufficient to attract and hold a diplomat of high order especially one who also possesses the skill of an engineer and the practical knowledge of an experienced farmer, it from necessity follows that there is more or less friction in the management. The man who can handle a large irrigation enterprise without complaints from the farmers can readily obtain a salary elsewhere far too great to justify his remaining on an irrigation work!

This condition must be borne in mind at all times in the operation and management of any work of this kind, which has to do with the untrained men working under pioneer conditions. Without any organization or means of control—each man is free to act as he pleases—planting his own crops in his own way, and at his own time. Under these circumstances, no system, however well planned, can meet the individual demands of the farmers. There must always be criticism and complaints which require the exercise of unusual patience and forbearance on the part of the management. It must not be supposed that because complaints are continually made, that the system is badly planned or poorly operated. The engineer himself must clearly distinguish between those criticisms which are important, or vital, and those which arise simply from having to do with a mass of humanity not yet educated by experience in that particular climate, soil, and surrounding.

Maintenance.—The maintenance of an irrigation system is theoretically distinct from the operation, but practically is very intimately connected with it, as the maintenance must be carried on in the same place and often at the same time with the operation.

Theoretically a canal should be operated during the crop season by a force proportioned to the number of distributions to be made and the number of miles of canals and laterals to be operated, and this force should report all defects, accidents, or worn-out apparatus, and as a result of this, the maintenance to be taken up as a separate item. As a matter of fact, however, it is economical and oftentimes necessary for the operating force to make many of these repairs or adjustments when they are discovered, although it is desirable to have what is sometimes called in railroad work "an extra gang" ready to go to any point to repair or renew structures needing attention.

The successful operation is dependent not only upon proper construction originally, but also upon immediate and effective maintenance of all of the structures. There is more or less depreciation at all times, and the gradual weakening of one part or another is sometimes of such a nature that the work can be done at almost any time during several months, or even years.

Successful and economical maintenance depends upon having accurate knowledge of the character and extent of the gradual as well as of the accidental depreciation, and of organizing the work so that immediate attention is given to breaks or critical places. At other times the men should be employed in improving the property where wear or decay is taking place, so that the maintenance cost may be kept at a fairly uniform rate.

It occasionally happens that a careful and competent superintendent who has thoroughly understood the work, and who for the good of the system has been forced from year to year to make certain expenditures in maintenance, is replaced by a man who desires to make a record for economy. The new management can cut down the maintenance cost notably for the time, but the inevitable result happens that the entire property depreciates in value, and in the course of a year or several years, breaks or accidents occur one after the other, the total cost of these being far greater than the apparent saving previously made. In comparing the cost of maintenance in different years or different systems, this fact must be always borne in mind, and careful analysis made to ascertain whether the maintenance has been careful and complete, or whether it has neglected some essential point, and exposed the system to larger loss.

Priming.—The expense of maintenance is materially affected by the care and skill shown in priming the canal, especially in skillfully bringing the water against all new works. Large amounts of money have been lost by lack of care in this regard, by attempting to use canals before they have been properly primed.

In the case of new banks, especially those which have not been thoroughly wet and compacted in construction, the water should be brought against them very slowly, being raised from day to day, and carefully watched. In the case of long sections of new or recently repaired canal, it may be necessary to provide temporary dams of timber and boards, or of sacks of earth, by means of which the water level can be raised a few inches at a time, watching carefully all possible locations where there may be signs of weakness, and reducing the water level at once, if leaks are discovered; at the same time puddling the points where there appear to be holes or pervious places. The points of greatest danger are at the juncture between the earth and the concrete, masonry, or wooden structures. Here extreme care must be used in bringing water against the points of junction, raising it with great slowness and with devices such that the level can be immediately reduced if there is any tendency to break through.

Care of Banks.—The maintenance of earthworks is a matter requiring continual vigilance. Nature is perpetually endeavoring to level down all surface elevations of this character, and most of the ordinary operations of men aid this leveling. Cattle tramping over the earth tend to loosen it, permitting the winds to blow it away, or cause it to roll down the slopes.

The canal banks frequently afford convenient roads and in many instances it is a matter of necessity for the men in charge of the work to travel on the canal banks. This has a certain advantage in compacting the soil, but it tends to make paths, or ruts, which catch the rain-water. If the banks are to be used for roadways, they should be made higher and wider than is required for canal purposes only.

The banks should be kept as symmetrical as possible, slightly crowned on top and sown with grass-seed, or the growth of grass and clover encouraged. Until plants of this character have taken possession, the larger and more injurious weeds rapidly spread, and it is necessary occasionally to cut these, especially those which break off when dry and blow into the canal.

In the warmer climates Bermuda grass has been tried and while this is very successful in protecting the banks it becomes a serious menace to the fields of the farmer under conditions where the frost is not sufficiently heavy to kill it during the winter.

Cleaning Canals.—It is necessary to clean most canals annually or oftener not only to remove the accumulated silt but under some conditions to get rid of the aquatic plants or moss, the latter term including a great variety of growth.

This so-called "moss" growing in the bottom of the canal forces the water to be carried above the normal level, presenting fresh surfaces of the canal bank to the water and increasing the losses by percolation, also the danger of breaks by the water finding its way into holes or points of weakness left by burrowing animals.

The destruction of this moss is a serious problem in some localities; the attempt has been made to prevent its growth by lining the canal with cement, but this is not wholly effective as shown by the fact that on the Twin Falls Canal in Idaho the only place reported as having trouble with moss is in a concrete-lined section where the velocity is stated to be as high as 10 ft. per second.

This moss does not grow rapidly in the shade but is troublesome where the water is clear and exposed to bright sunlight. In some localities cottonwood or other quick-growing trees are planted along the canal in order to provide a shade in the hopes that within two or three years the shadows from the trees will be sufficient to practically prevent or to a large extent control the growth of moss.

Mowing machines to be drawn through the canal by horses walking either in the water or on the banks have been devised. These cut the aquatic plants while the canal is full of water or in operation and as the material rises and floats away, it is caught and pulled out upon the bank. Heavy chains are also drawn along the canal bottom tearing loose the plants or in some instances a metal band with teeth or "moss saw" is used to cut or tear the aquatic growth. Wherever it is practicable to rotate or alternate in the use of water, the canal bed is left dry a few days, so that the sun will destroy the weeds; but on the main canal this is not possible.

The vegetable growth in irrigating canals include many species of algæ representing such genera as Spirogyra, Stichococcus; Microspora, Ulothrix, etc., occurring in flowing water of canals. In still water these may usually be eradicated with little or no difficulty by the application of a small quantity of copper sulphate. The different species vary greatly in their susceptibility to this poison; some species are readily killed by an exposure of two to four hours to a solution of one part of copper sulphate to twenty million parts of water, while others resist for several hours a concentration of one part of copper sulphate to one million parts of water. In addition to these susceptible algæ other plants such as Potamogeton, Chara, etc., sometimes appear in canals, and are too resistant to the action of chemical agents to be eradicated by such means.

Organization for Operation and Maintenance.—The organization for operation and maintenance depends largely upon the size of the system and its complications. A small system can be operated by a very few men, as is the case with a small railroad, where it makes little difference whether absolute accuracy as to time and service is observed. With the large irrigation system, however, embracing thousands of farms, where every small error in judgment may result in losses to hundreds of individuals, far greater care proportionally must be given to a system, and the expense is correspondingly increased, the organization being more highly specialized and adapted to the greater demands made upon it.

The object of this organization, and in fact of the whole works, is to deliver water promptly and in necessary quantities. Reliable service is of the highest importance—far more than cheapness of operation. With good management the crop returns are so large, and with poor management so disappointing, that the irrigators have less concern about the cost than they have about the efficiency.

At the head of the organization must necessarily be the manager, who must oversee the general system, decide all questions in accordance with the laws and regulations, and settle the innumerable controversies which are inseparable with delivery of water through open channels. Under the project manager are usually two or more superintendents, who in turn have oversight of a sufficient number of water masters or canal riders to enable the entire system, including hundreds of miles of main and branch canals to be traversed once or twice each day.

In an irrigation project with farms of ordinary size the irrigated acreage in each being from 40 to 60 acres or more, one canal rider is required for about 3,000 acres. If every delivery is to be visited each day the number of canal riders will be materially increased and in case the holdings of 80 or 160 acres each the number can be reduced.

The wages paid to canal riders generally range from $75 to $80 a month and may go as high as $90 or $95. In most cases local men are employed, the more important men being kept throughout the year and the others for six months or during the irrigation season. Each canal rider is required usually to furnish his own horse and has frequent need of an additional animal to allow suitable rest, as the daily average ride is from 20 to 25 miles. The water masters are paid usually $125 to $150 a month and supervise eight or ten or more canal riders. There is also a clerical force the size of which is dependent upon the detail with which the records are kept.

Records.—Accurate records are as essential in the proper operation and maintenance of a system of water supply as they are in other business. Without them there is continual uncertainty with resulting controversies, and although it is not possible to settle all claims by reference to the records, yet most of these are quickly adjusted by having the facts correctly stated. The principal records are those which show the amount of water entering and leaving the reservoirs day by day, the dates, and quantities taken into the canals and distributed to each branch or lateral, and finally turned to each wateruser. These records give by comparison the losses by evaporation and seepage, call attention to possible thefts of water, and form a guide by which the manager from day to day controls the system.

In addition to the water measurements, it is necessary to have records of acreage and of crops—these being revised at the beginning and end of each crop season in order to obtain data concerning the use of water, and prevent unlawful diversion from one field to another.

Costs.—There are few reliable figures of cost of operation and maintenance, this being due largely to the fact that there have been no general agreements as to the character of items which are to be included in this. As a rule it may be said that the small systems operated by the farmers apparently cost them from 50 cents to 75 cents per acre per annum, and sometimes less; but it is not possible to ascertain whether all of the overhead charges have been included in this, as much of the work is performed by volunteer services, and is not made a matter of record. The larger systems where better records are kept apparently cost from $1 to $1.50 per acre for operation and maintenance, not including in this the depreciation or cost of larger repairs due to catastrophies.

As a rule it may be stated that the less the cost, the poorer the results, and the larger the losses on the crop returns. For every 10 cents per acre saved in the apparent cost of operation and maintenance, the ultimate crop production may have been reduced from $1 to $10.

In examining the history of many of the private enterprises, it is extraordinary to see how, through neglect or by false economy, water has been kept out of the canal during critical times of the year, with resulting crop losses aggregating tens of thousands of dollars, these being regarded by the farmers as dispensations of Providence rather than as a result of their own ignorance or lack of organization. It has been no uncommon thing for a large canal to be deprived of water for a week or ten days during the extreme heat of summer, and the crops on 10,000 acres reduced in value by at least $5 per acre—this loss resulting simply from an endeavor to save a few hundred dollars in the management.

In keeping records of cost, the first or most obvious classification is under the two heads of "operation" and "maintenance." It is necessary to distinguish somewhat arbitrarily between these as one merges into the other. There is also a third class of items, which is sometimes considered, namely, betterments, which really belongs in part in the original construction cost, but which being incurred after the canal system is practically finished, must be carried as a part of the maintenance or upkeep.

The operation costs are usually considered as including those items which pertain to the distribution of water to the individual farmers, as distinguished from the maintenance which relates to the expenditures having to do with the preservation of the system.

Each of these two classes of expenditure may further be divided into the principal features of which a canal system consists, namely, *first*, storage or reservoir division; *second*, the diversion dam and headworks; and *third*, the main or trunk line canal and principal branches; *fourth*, the lateral or sub-lateral system leading from the larger branches to the individual farms.

In turn again, these items consist of expenditures for supervision, labor, materials, supplies, etc. Thus carried to the extreme, the cost-keeping system should show the expenditures, for example, in labor or materials in operating the diversion dam and headworks, or in maintaining the main canal.

CHAPTER X

STORAGE WORKS

Determination of Storage Supply.—The question of storage must be considered sooner or later by the engineers of any considerable irrigation system. It is true that the earlier canals taking water from perennial streams, and having first rights to the natural flow, may have adequate supply for most of their lands, but as the country develops even these canals may be extended or enlarged. The extent to which this can be done depends upon acquiring additional waters, since the rights to water for new lands is secondary to those of lands which have been previously irrigated. Thus it is that the matter of conservation of the floods, and of the waters which occur at periods of the year when not needed for irrigation becomes very important.

In attempting to arrive at a determination of the storage supply, there are several factors which must be taken into account. The first question is relative to the total quantity of unappropriated waters, and the second has to deal with the character and capacity of reservoirs feasible to construct within reasonable limits of cost. It is necessary to consider also whether the floods occur at such times and in such a manner that they can be controlled.

In every case the question of probable cost is important, and involves taking into account the quantity of water required for the lands under consideration; the latter is governed largely by the character and location of lands, as well as the area to be watered.

In practically every case engineering and economic questions are involved, the former dealing with the physical conditions of runoff and topography, the latter, with cost of conserving and value of the supply.

Annual Runoff.—Of the engineering questions involved in storage, the first and most quickly answered, if measurements of the stream are available, is as to the annual runoff, or total quantity of water which has occurred in the stream each year in the recent past. It is obvious that this quantity limits all future development, unless the drainage area can be increased by bringing into it one or more streams from another basin. The annual runoff varies largely from year to year, and in any one year may be several times that of a measured year, or it may be far less.

There are also to be found, in studying measurements of runoff for consecutive years, that in some one year there were practically no floods, and that such a year may be preceded, or succeeded by a season of drought, as dry years frequently occur in succession. There are also to be expected other years when the floods surpass those in the memory of the oldest inhabitant, and when structures which were planned to meet ordinary conditions may be swept away. In other words, all proposed works for storage must be considered with a view to the fact that they must meet extraordinary flood conditions, and may occasionally not receive much, if any, water for storage.

There have been in the past many efforts to find some simple rule connecting the amount of rainfall as measured on the drainage basin with the quantity of water flowing from it. Some engineers have assumed that the runoff would be a trifle less than one-third of the rainfall. The attempt to apply such a rule, however, under different topographic and climatic conditions, has led to absurd results, as in the arid west, the runoff may not exceed 2 or 3 per cent. of the rainfall as measured on the higher portions of the catchment area. The runoff in any one year, especially that of unusual rainfall may rise to 10 or 12 per cent. over the entire watershed, or in a year of drought drop to less than 1 per cent. (For further discussion see chapter on Water Supply.)

Amount of Runoff that can be Stored.—Not all of the water shown by the measurements of river flow is available for storage. The records of river flow usually show that a certain quantity of water has passed a given point on a stream during certain seasons of preceding years. It is frequently assumed that all the water can be held, and many unwise investments have been made because of the fact that extensive works have been constructed, based upon the assumption that all the water known to occur in the recorded floods could be held in storage basins.

The limitations upon the amount of water which can be economically stored are those arising from two causes; first, geographical, or topographical; and second, hydrographic. Under the first are included those which pertain to the relative position on the drainage area of the storage basins. The best of these are usually found relatively high up on the stream or on its tributaries, and in such positions that the amount of flood water occurring above the dam site is relatively small. In other words, the greatest floods occur at points below those at which feasible storage sites are found. It may be said to be a general rule that the better the physical conditions for a reservoir site, the less the amount of water available at that point. In nature we frequently find broad valleys with relatively narrow outlets through which flow insignificant streams, with small, or irregular floods; and, on the other hand are large streams with considerable volume flowing through narrow, deep valleys, with fall so great that storage reservoirs are out of the question.

These hydrographic conditions limiting storage are those which arise in accordance with the volume and rapidity or intensity of the flood and in the manner in which one flood may follow another in immediate succession. If a large reservoir is located on the main stream, it will, of course, catch all of the flood coming into it up to the capacity of the reservoir; but if, as is occasionally the case, the storage reservoir is on a side stream, and the floods in the main stream must be diverted by a flood water canal, then the amount of water which can be brought into such a reservoir is limited largely by the capacity of this flood canal. If the floods occur somewhat slowly, and do not exceed the capacity of this diversion canal, the maximum amount can be stored; but, if the flood is flashy, with a high peak exceeding the capacity of the canal, then a correspondingly less amount can be conserved.

It frequently happens that droughts succeed droughts, and floods follow floods, but in operating reservoirs, it is usually assumed that the first flood will be caught, and held to the full extent. If, then, there happens to be a second flood following upon the first, while the reservoir is still full, and before it can be drawn down for storage elsewhere, or for beneficial use, then it follows that the second flood is largely wasted. Thus it happens that although on casual inspection of the data of river flow there appears to be a large volume of water, yet careful study of the limitations frequently lead to disappointing results, because of the fact that only a small portion of the total amount of water can be economically held.

Each stream or catchment area must be studied by itself, with reference to the location and capacity of the proposed storage sites, and of the relation of these to the particular part of the drainage area tributary to each storage basin. The prior appropriations, or legal claims to flood water, which may exist, and the rapidity of the occurrence of floods, must also be studied carefully with reference to these particular sites. As a result it is frequently necessary to exclude from consideration large and important parts of a drainage basin because of the fact that these parts are not tributary to any economical reservoir site.

Ordinarily it may be said that the building of a reservoir of sufficient capacity to hold all of the flood waters from a given shed is impracticable, both from a physical and economic viewpoint. It consequently becomes a question of determining the greatest amount which can be economically held. To do this, it is sometimes necessary to consider carefully the future need for water and its probable value.

Seepage Losses.—The full or theoretical capacity of any reservoir is not always the amount which can be depended upon for beneficial use. There are certain losses which must be taken into account, and occasionally some gains. The principal losses are grouped under the headings (1) Evaporation, and (2) Seepage.

The evaporation losses are practically continuous and so far as present knowledge goes, cannot be controlled at reasonable cost. If it were practicable to cover the reservoir to exclude sunlight and wind movement, they could be reduced to a minimum, but the necessary expenditure for this purpose would be prohibitive. In cases where the spring floods are held in a reservoir and the water is drawn down during the succeeding summer, these losses are usually not very serious. Under these conditions there are only three or four months of evaporation to consider, but if the reservoir is to carry water over to years of drought, then the total annual losses come into play and these usually form a large proportion of the amount stored.

The seepage losses are frequently matters of great concern but unlike the losses of evaporation there is a tendency for these to gradually reduce by the lapse of time due to the silting up of the bed of the reservoir. In new construction, where water is being held for the first time in basins which have not been thoroughly wet for centuries, the seepage losses are very great. Each year as the reservoir is filled higher and higher and newer lands are submerged, these losses continue, but as the underlying soil becomes packed through the presence of water and layers of fine silt are deposited on the bottom, there is a tendency to render the underlying earth less pervious and to prevent the free escape of the water.

The accompanying diagrams illustrate some of these conditions of losses of water from recently built storage works. They are especially instructive as showing the actual conditions. In these

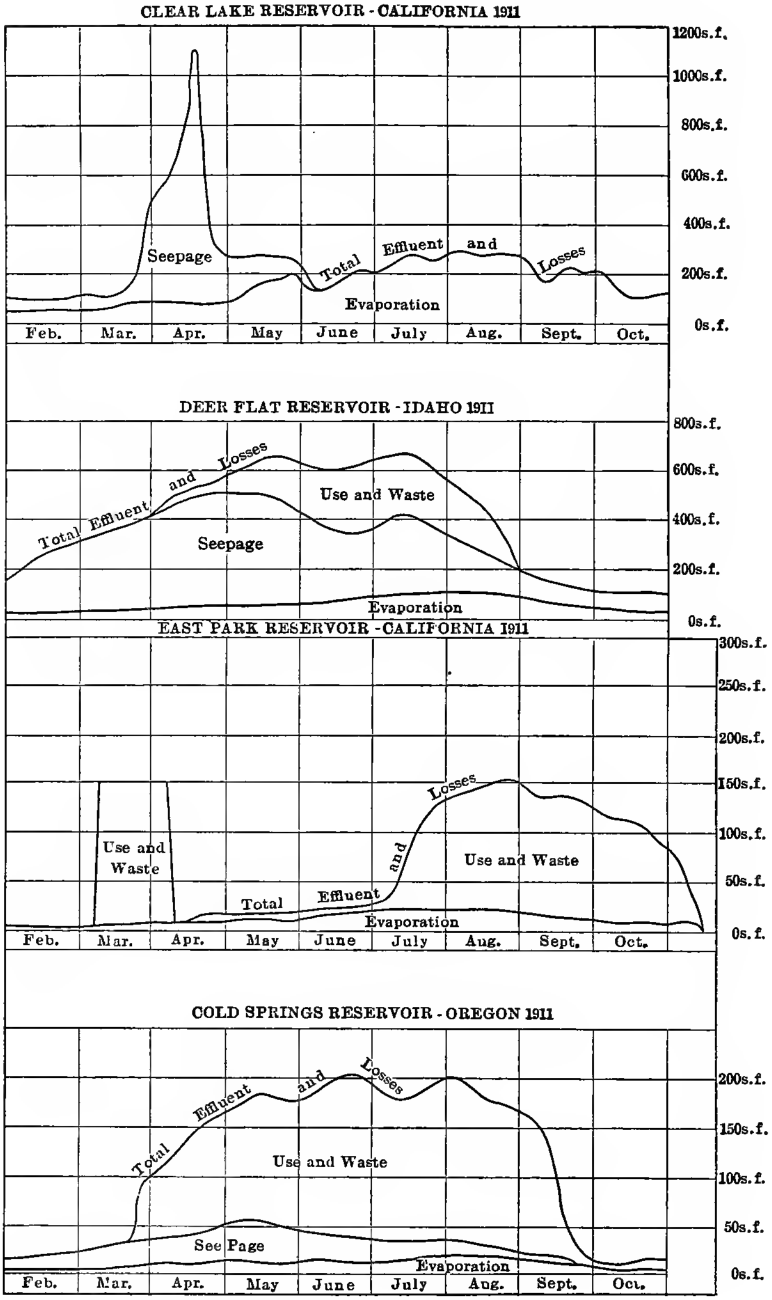

FIG. 37.—Diagram illustrating losses in reservoirs.

comparison is made between several reservoirs of distinctly different geologic structure; for example the East Park Reservoir in the Orland project, California, is in a basin in crystalline rocks in the mountains where the seepage losses are probably at a minimum, while the other reservoirs noted are in a region of lava flow. In the case of the East Park Reservoir evaporation may account for most of the water which disappears. In comparison with this is to be noted the Cold Springs Reservoir of the Umatilla project, Oregon, which is in a basin cut in eruptive rocks of large porosity, these being overlaid with somewhat heavy beds of sands, gravel, and wind-deposited materials. Still larger losses are shown in the Clear Lake Reservoir of the Klamath project, Oregon-California. This has been built partly for the purpose of reducing the floods in Lost River and where the seepage losses into the underlying lava were anticipated as being large. Greater losses are shown from the Deerflat Reservoir in Boise project, Idaho, where water storage is provided out on the rolling plains and where the lava is covered with a relatively thin layer of soil, these seepage losses are being steadily reduced year by year but will probably always form a notable percentage of the amount of water stored.

Evaporation Losses.—Every body of water, large or small, exposed to the sun and wind, is constantly losing from the surface a greater or less amount, which is dependent mainly upon the temperature and wind movement, and to a less extent upon other causes—such, for example, as altitude and atmospheric conditions as regards moisture. In the case of natural reservoirs, spread over hundreds of acres, with exposure to winds which sweep down the mountain, and with a hot sun pouring from a cloudless sky, the losses are very great, and become a notable percentage of the quantity stored. These losses have been the subject of prolonged study by various observers—notably those of the Weather Bureau, and officials in charge of important city waterworks.

As yet the laws governing evaporation in large bodies of water are not fully understood, nor reduced to exact statements. For the present the engineer must base his assumptions upon the more or less empirical formulæ, or arrive at them from direct comparison with observations of the rate of evaporation under similar conditions of climate and topography.

The evaporation during the summer season with its higher temperature is, of course, greater than during the winter, although there is an appreciable loss during the cold weather, even from the frozen surface of the lake. The losses from the surface of a broad shallow basin are also greater than those of a deep body of water, because of the higher temperature of the shallow waters. The wind movement also has a very important effect, in that it carries away the moisture-laden air immediately over the surface, and permits a more rapid rate of change from liquid to vapor.

The following table illustrates the difference in rate of evaporation month by month, under different local and climatic conditions. It is given merely as an illustration, and as demonstrating that the loss by evaporation is large:

DEPTH OF EVAPORATION IN INCHES, BY MONTHS

Month	Neb.	Idaho	Oregon	Lake Tahoe	Nevada	Wash.	N. Mex.	Arizona
Jan.	1.75	1.50	0.50	1.75	1.75	1.75	2.50	4.59
Feb.	1.75	2.25	1.25	1.75	1.75	2.50	2.75	4.75
Mar.	3.00	4.00	3.27	1.75	2.25	6.25	4.50	6.25
Apr.	4.50	7.25	6.64	2.00	3.25	7.91	8.00	9.00
May.	6.25	10.68	7.15	3.00	5.25	8.36	11.50	11.50
June.	8.05	11.05	6.99	5.00	7.86	8.90	13.45	13.50
July.	10.95	11.15	8.01	6.49	9.86	10.74	11.57	14.25
Aug.	9.39	11.77	9.21	7.42	8.70	9.41	10.48	14.23
Sept.	7.44	9.75	6.13	7.75	5.13	5.51	8.58	13.76
Oct.	5.59	5.40	2.50	4.33	3.35	3.15	6.76	11.31
Nov.	4.00	2.70	1.00	3.13	2.50	2.00	3.86	7.39
Dec.	3.00	1.50	0.50	2.25	2.00	2.00	3.00	4.65
Totals.	65.67	79.60	53.45	42.21	53.65	67.96	86.95	115.18

The above figures of depth of evaporation are probably the results of observation by Professor Frank Bigelow of the U. S. Weather Bureau (Engineering News, Vol. 63, p. 694, June 16, 1910). Many of the figures are interpolations, but they represent the results of observations of evaporation—not from reservoirs, but from pans, usually 4 ft. in diameter, located on the ground. The losses from a large body of water may be more, but presumably are less. Observations indicate that there is a nearly uniform rate of evaporation over the area of the water surface of a lake or pond, beginning at a short distance from the shore.

It should be kept clearly in mind that these figures, and similar figures frequently quoted, represent the losses from relatively small areas, and not from the lake surface itself. There is a very great difference in the amount of evaporation from pans placed side by side, depending upon their diameter and height of rim of the pan above the surface of the water; and there is no known relation between the evaporation from a pan of a given size and an open body of water; the losses in each case may be greater or less, dependent upon many conditions.

In looking over these figures, it is to be noted that although the total evaporation for the year may be approximately the same for different localities, the distribution of this by months is variable, dependent upon climatic conditions prevailing at the time. For example, in Oregon observations of winter evaporations show a remarkably low loss as compared with the others. All show a maximum in July or August, the rate of evaporation dropping off rapidly after these months.

The effect of evaporation in reducing available storage capacity will depend upon the size and depth of the reservoir, and also the length of time that water must be held in storage; that is to say, the percentage of loss from a large, shallow reservoir is far greater than from a small but deep one of equal capacity; also, the relative loss from a storage supply held during a single irrigation season will be far less than if water must be held over from one year to the next.

The losses by evaporation of 6 in. in depth during a month of thirty days, on a reservoir having a surface area of 3,000 acres is equivalent to a steady flow throughout the thirty days, of approximately 25 second-feet.

Ratio of Runoff to the Storage Capacity.—The relation which the total runoff or amount of water delivered from a given drainage basin bears to the storage possibilities is one of the first objects of concern to the engineer interested in the conservation and development of a water supply. As a rule it may be stated that the larger the runoff per square mile drained, the less the probabilities of finding good storage sites. This is because of the fact that with large runoff the streams through past ages have eroded their channels and have carved broad outlets through various obstructions, making it difficult to create artificial basins. On the other hand, with reduced runoff per square mile, the streams have become overloaded with sand and gravel; their beds are now choked and they have not been able to cut such outlets in the natural barriers. This general rule is, of course, modified by geologic conditions, especially where ancient glaciers have built morains across the valleys, or where there has been the tilting of the earth's crust in one direction or another, changing the former slopes and bringing in new complications.

The amount of total runoff is a quantity which cannot be modified appreciably by man. It varies from year to year according to the climatic oscillations. The portion of this which may be put to beneficial use is, however, dependent quite largely upon human agencies. It is assumed to be practicable to begin systematic forest protection at the head-waters, and thus exercise a beneficial influence upon the way in which the runoff comes from the steep slopes. It is now generally believed to be essential to the full conservation of the water supply that the catchment areas of the streams be studied and controlled with reference to the covering of trees, shrubs, grass, etc. Assuming that this is done, and that the violence of extreme floods, or the rapidity of runoff is modified as far as practicable by good forest and grazing conditions, then the question next in order is that of proportion of the water flowing in the stream which can be controlled.

On most streams within the irrigated region, the ordinary summer flow has already been appropriated and put to beneficial use. Canals have been built with capacity sufficient to take all of the normal flow during the crop season. Assuming that this is the case, the next question is with reference to the waters which occur in the stream at times other than during the crop season, and also of the floods which take place in the spring or early summer, and which exceed in volume the capacity of the canals already built.

All of the water which flows before and after the crop season, or at the times when not actually needed for irrigation during the season, should be held for use later, and under ordinary conditions it may be considered as available for storage. However, there has recently grown up a practice which has resulted in some doubts and legal controversies. Some of the oldest appropriators are attempting to use the fall and winter waters for flooding the farming lands after the crops are removed, with the idea of saturating these lands as far as possible, in order to reduce the amount of water needed during the succeeding crop season. There are a few conditions of soil and climate where this can be done effectively, but there is always a question as to whether this is not a wasteful use of water. In the case of heavy, or loose gravels underlying the soil, it appears probable that even though these gravels are filled with water during the fall and winter, yet before spring they will drain out and the benefits derived will not be comparable with the resulting waste. Because of this condition, conflicts have arisen between the reservoir men on the one hand claiming that they are entitled to this water out of the crop season, and the farmers on the other, who claim that they are entitled under their appropriations to all the water they desire to use throughout the year, and that they should be permitted to store it in the ground in the manner described.

Regarding the floods, there has been no serious question as to the fact that the portion of these in excess of the capacity of the irrigating canals should be stored. These floods usually occur at the beginning of the crop season, and hence the length of time during which they are stored and the consequent losses by evaporation, are at the minimum.

Determination of Storage Required.—Having ascertained the limitation of the possible storage set by physical conditions, such as quantity of water, and capacity of feasible storage basins, the succeeding questions are generally easily answered, because it is usually assumed that the entire available quantity, extreme flood excepted, will be held for future use. It occasionally happens, however, that the area of irrigable land which can be reached from any one storage reservoir, or system of reservoirs is limited, and in that case the question is narrowed to the actual needs of this particular tract of land. It is, of course, not economical to go to the extreme of providing more storage than is actually needed, and on the other hand the possible crop losses will not justify providing inadequate storage.

Theoretically, the storage reservoir should be of such capacity that it can be drawn upon whenever needed to supplement the ordinary supply received from the unregulated flow of the stream. Nearly every irrigable tract is enabled to obtain water from a perennial or intermittent stream, flowing during the early part of the crop season and the storage reservoir is intended to supplement this supply. In some cases, however, this is so irregular that the storage reservoir must be large enough to take care of the entire tract.

The first question, therefore, is: What dependence, if any, should be placed upon the natural flow? This varies greatly from year to year, and in any period of ten or twenty years there is some one year which is much lower than all the rest. Under the existing crop conditions, is it economical to make provision to take care of this exceptionally low year, or will the expense of so doing not justify the results? In other words, is it not better to figure on reduced crop production during this one year than to make extraordinary provision for it? In such case, knowing in advance that there may not be enough water, the farmers are warned to economize the water in saving the trees, and to take their risks upon the least valuable of the annual crops. This question of economical importance of crop failure one or more years in every ten must be balanced against the probable cost and practicability of providing against the exceptional year.

Having made certain assumptions as to the requirements of minimum years, there then follows the assumption as to the amount of water which can be depended upon by natural flow, if any, during these years, and the amount which must be stored to provide the supplemental supply. The assumptions of minimum year requirements will, of course, vary under different conditions of climate and character of crops to be raised. Under certain conditions, it may be assumed that for one year in ten, or twenty, it will not be economically possible to provide a complete supply. This may be justified by the fact that the losses during that one year will be more than balanced by the saving in the cost of storage works.

This minimum flow does not occur throughout the crop season, but for certain months, or portions of months; and for the other months it is not necessary to provide the same amount of storage. That is to say, from day to day there will be a greater or less quantity of water available from the stream, and there will be a greater or less demand for this, according to the needs of the crops. The difference between the probable amount which can be had from the stream, and the probable regular demands from the farmers, measures the quantity which should be available in the reservoir.

The sum total, however, of these daily demands upon the reservoir do not by any means measure the storage required. This must be increased to meet losses:

(a) by evaporation which is dependent upon length of time stored and climatic conditions;
(b) seepage in the reservoir itself;
(c) losses of water in transit from the reservoir to the lands;
(d) other losses, often unaccountable, mainly due to improper methods of handling and distribution.

The storage capacity also is modified by the fact that there is more or less accumulation in the reservoir due to irregular storms, at the same time that these losses are occurring, so that we have a constantly fluctuating burden to be carried by the reservoir.

The amount of storage required, as is obvious from the preceding statements is not a simple matter directly comparable with the acryage to be served; first, because this acreage may be supplied in part be a fluctuating flow of the stream; and, second, because its requirements for water vary from day to day. As far as practicable, a schedule should be made in advance of the probable needs of the land, depending upon the character of crop, and the time of year when the various crops require certain amounts of water. If most of the fields are in alfalfa, this will require water at intervals of two or three weeks throughout the entire growing season, or even late in the fall; whereas, if more of the land is in wheat or smaller grain, and this is not followed by another crop, the irrigation may be finished early in the summer, and largely by waters taken directly from the river.

In considering the question of storage, therefore, it is necessary to assume what are, or will be, the principal crops of a region, and the time of year when these will probably be irrigated. In other words, make certain assumptions as to the total amount of water which should be delivered day by day. From this is to be deducted the probable amount which may be obtained without regulation from the natural flow of the stream, including floods. The difference represents the deficiency which should be supplied by storage on the given days or periods of time, and a study of these probable daily demands will show that the reservoir need not be planned with reference to the entire amount of water which will be used during the year, but rather with reference to a fluctuating quantity. The problem thus is not one of simply ascertaining the details for the year of river flow, and of water to be applied to the land; but, on the contrary, that of an analysis, day by day, of the varying quantities—each modified by climatic conditions as regards supply and probable crop conditions, as regards needs of water.

Economic Questions in Storage.—Water storage for irrigation is relatively a new subject as regards the economic considerations. Irrigation itself is as old as civilization, and the questions of canal construction and the diversion of the water to the land by gravity are fairly well understood. Water storage for agriculture also has been practised to a certain extent, especially in India, but there has not yet been developed a consistent theory, or set of rules, based upon economic considerations. Each case of storage has been considered by itself with reference to local conditions, probable amount of money available for expenditure, the works being built accordingly and then modified on the basis of further experience.

Theoretically, water conservation by storage should be extended to a full limit of the amount of water which occurs in nature. As a rule there is more good land needing water than there is water to supply it; and wherever this holds true, it would seem to follow that every drop of water should be held to irrigate the lands. There comes in here, however, the question of cost. To take an extreme case, there will be in a given period of twenty years one excessive flood. The waters of this flood cannot be held indefinitely in a basin, because they will escape by evaporation. Even if any considerable part could be held, the question arises as to whether the cost of providing a large enough basin would be justified by the value of the waters, coming, say once in twenty years. The agricultural development of the country could not be economically adjusted to utilize this irregular supply, especially as the time of occurrence could not be known in advance. In short, by considering an extreme case, it is recognized that there are few conditions where all of the flood waters can be economically held. We must, therefore, figure on holding less than the total flow, especially in the extremely wet years.

Coming down the scale from the excessive floods, we finally reach a place where it becomes an evenly balanced matter of cost and benefits; that is to say, the floods which occur every year, or four years out of five, should undoubtedly be saved, if possible, because for the fifth, or dry year, some water may be held over, or the area of annual crops can be reduced. Starting from the other extreme, it may be also said that storage should not be neglected, because there are known to occur certain years, once in ten or twenty, when there are practically no floods. It would be unwise to assume that because such a year occasionally occurs, therefore, no storage should be provided.

We thus have an intermediate point somewhere between these two extremes—namely, that storage in general should not be considered for extreme floods; nor should it be limited to the minimum flood.

A determination of this intermediate point rests upon crop values immediate or prospective. If the climate is cold and the principal crops are such as to bring but low returns per acre, then there is little justification in making a large expenditure for the storage, such as would be practicable and desirable in warmer climates, where crop follows crop in rapid succession and where the unit value per acre of crops is large.

The immediate, or present value of the crops produced in an area should not be used as the limiting feature, because it is proper to assume that with more complete development of the area, there will result larger crop production, and better facilities for marketing and handling this. It is also safe to assume that ordinarily when the country is developed, there can be no over-production in the sense that such large quantities of crops will be produced that the value will decrease. This condition may exist temporarily, but with irrigated lands forming such a small percentage of the arid west, this condition cannot be permanent; hence, it is desirable to use a reasonable optimism with regard to future crop values, basing these not upon the temporary conditions of extremely high or low values, but upon those which may be considered more nearly normal.

Cost of Storage.—From what has been stated before, it is apparent that in this, as in other operations, the determining factor in water storage is cost; both absolute, as dependent upon the amount of money available, and relative, as regards the benefits which may be derived. To illustrate this point, we may consider two extreme cases: If the area under consideration is capable of high development, or is practically suburban in character, with genial climate, such as that of the State of California, the conditions approach those of water storage for a city where almost any amount of money can be expended, the cost of storage of $100 per acre-foot may not be beyond consideration.

On the other extreme, where the lands to be supplied are mainly used for forage crops, the cost of storage of $5 per acre-foot may give rise to hesitation. Between these two there is a wide range of amounts which may be considered. The following table gives some costs which have actually been incurred. In arriving at these the total capacity of the reservoir is taken, irrespective of the fact as to whether this is filled each year, or whether it is increased by serving as a temporary or regulating reservoir, as for the present purposes, it is assumed that each reservoir has been built to its maximum feasible capacity.

COST OF RESERVOIRS COMPLETED BY UNITED STATES RECLAMATION SERVICE, DECEMBER 31, 1911

State	Name of reservoir	Available[1] capacity	Cost to December 31, 1911	
			Total	Per acre-foot
Arizona	Roosevelt	1,284,000	$3,746,696.41	$2.92
California	Clear Lake	462,000	127,408.61	.28
California	East Park	45,600	264,929.66	5.82
Idaho	Deer Flat	173,000	904,542.68	5.22
Idaho	Lake Walcott	150,000	569,278.86	3.80
New Mexico	Hondo	40,000	154,019.19	3.86
Oregon	Cold Springs	50,000	442,786.10	3.84
S. Dakota	Belle Fourche	203,770	1,242,438.77	6.12
Washington	Conconully	13,000	328,169.26	2.52
Washington	Bumping Lake	34,000	429,121.13	12.60
Wyoming	Pathfinder	1,025,000	1,739,675.81	1.70
Wyoming	Shoshone	456,000	1,191,734.21	2.62
Wyoming	Snake R. Storage	380,000	441,023.04	1.16
Grand totals		4,316,370	$11,582,649.21	Average 2.70

[1] Acre-feet.

CHAPTER XI

RESERVOIR SITES

General Requirements.—A good reservoir site, from a purely topographic standpoint, may be considered as one where a broad valley or expansion may be permanently closed by a dam of reasonable dimensions. In order, however, that such a site may have value for storage purposes, a water supply is also necessary. In his search for a reservoir site the engineer must, therefore, confine his attention to the valleys of streams of undoubted water supply, or to near-by valleys into which such streams may be diverted.

The capacity of a reservoir which may be formed at a given site, compared with the mean annual runoff at that point, is also a matter of some importance. It is obvious that to construct a reservoir so large that it would be filled but once in twenty years, or possibly not at all, would involve a useless expenditure. On the other hand, a reservoir so small that it would hold only a portion of each year's runoff would, in general, cost more per unit of capacity than one of larger size.

The ideal reservoir site is one which can be economically constructed to a capacity sufficient to hold all of the runoff from its tributary watershed, except that from extraordinary floods which may come once in ten or twenty years, or possibly at less frequent intervals.

It may sometimes occur that the amount of storage capacity required is limited by the area of irrigable land in the immediate vicinity. What is wanted in this particular case is not the most economical storage for the entire stream's supply, but the most economic for the capacity required. In such cases there are frequently a number of sites from which to choose. Even in such cases consideration should be given to possible future developments, and other things being equal, or nearly so, preference given to the reservoir site whose capacity may be increased to meet possible future needs.

Good reservoir sites like good gold mines are scarce, and as in the case of gold mines there are almost innumerable prospects which are popularly supposed to be valuable but which, upon further examination, prove to have some fundamental defect. In beginning a reconnaissance of any area, the inhabitants of that region will call attention to the innumerable localities where in their opinion water might be held, but at a glance an experienced engineer will see that usually the capacity of the basin is too small to justify the cost of a dam because the floor of the valley is usually found to slope at such a high angle that little, if any, water could be held behind a dam of moderate height. To the uneducated eye the valley may appear to be level.

Survey of Reservoir Sites.—Before entering upon definite surveys it is necessary that a reconnaissance be made of the entire lower portion of the area or watershed of the stream to ascertain roughly the relative value of the various possibilities. For the purpose of this reconnaissance the very best field man of largest experience is none too good. It is his duty to weigh carefully the apparent advantages and disadvantages of each locality and then recommend definite surveys. As all such surveys involve the employment of a considerable number of men and are quite expensive, it is incumbent upon the man making the reconnaissance to judge accurately and thus avoid as far as possible useless surveys or examinations involving merely negative results.

After it has been found by careful reconnaissance that the choice of the reservoir sites is narrowed to a relatively few places, then arrangements should be perfected for a careful topographic survey resulting in a contour map of the storage basin. This map should ordinarily be made with sufficient accuracy to determine the capacity of the basin to within 5 per cent. Greater accuracy than this is generally not necessary but in some cases is desirable.

The map of the reservoir site should be made on a scale of from 1,000 ft. to 2,000 ft. to the inch, dependent upon the size of the basin and nature of the topography, the scale being chosen so as to afford reasonable accuracy for each particular case. At the site of the dam, however, where excavation is to be undertaken and where large expenditures are made, it is necessary to have a far more elaborate map than for the rest of the reservoir. Here a scale of from 100 ft. to 400 ft. to the inch is desirable. In Fig. 38 is given a portion of such a map with contour interval of 5 ft. and the final location of the dam with related works sketched upon it.

These surveys may be made most quickly and economically by means of the plane-table, if the engineer in charge is accustomed to the use of that instrument and can sketch accurately and rapidly.

If a plane-table man and necessary instruments are not readily obtainable, the survey can be made by the slower and more expensive way of running out contours or marking cross-sections and locating these by transit and level and then sketching in the contours from these somewhat accurately determined points.

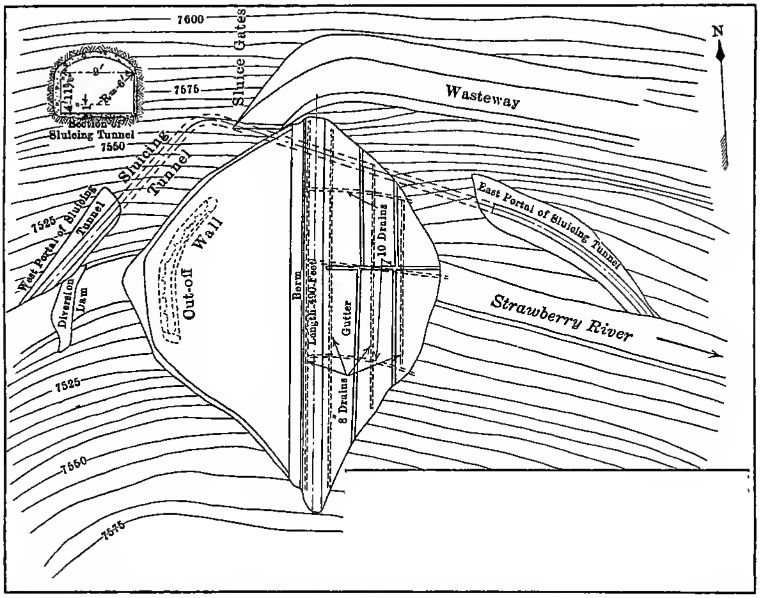

FIG. 38.—Portion of topographic map of dam site with related works sketched upon it. Strawberry Valley Project, Utah.

Contour Maps.—The contour maps which result from the various methods of survey should be drawn on a scale as above indicated and should show sufficient detail to enable a thorough study in the office of the essential features. For this purpose the contour interval of the reservoir basin unless this is very large, should be 5 ft. and of the dam site should be 1 or 2 ft. All rock outcrops, especially near the dam site, should be indicated and all cultural features such as roads, buildings and fences clearly shown, together with the character of vegetation and of soil. Information of this kind is needed, not only in connection with the engineering features, but in adjusting claims for damages, rights-of-way or interference with public travel. In fact there is hardly any detail which can be shown on the map but which may be needed in determining the value of the reservoir and in making plans for constructing and operating it.

Computation of Capacities.—The capacities of a reservoir site at various elevations of water surface are determined from the contour maps. As a rule the area enclosed by each contour is measured by a planimeter, the results being determined in acres. The mean of the area in acres between any two contours multiplied by the vertical distance in feet between the contours gives approximately the capacity in acre-feet. The mathematical inaccuracy of this method is no greater than that involved in ascertaining the exact area of the water surface at the different elevations.

In cases where accurate contours have not been drawn but cross-sections run at short intervals the capacity may be determined by taking the mean area of any two sections and multiplying this by the distance between them, the sum of the various elements thus determined being the total capacity. Results obtained by this method are usually in cubic feet which may be reduced to acre-feet by dividing by 43,560.

At the bottom of the reservoir is frequently a dead space, that is, water below a certain elevation dependent upon the location of the lowest workable gates, is seldom if ever drawn upon. This dead space is in time filled with sediment if the water is muddy. A deduction should be made from the theoretical capacity of the reservoir, allowing for this unavailable capacity.

Choice of a Reservoir Site.—It occasionally happens that there is opportunity for choice between different possible sites. As a rule, however, good reservoir sites are so rare that there is only one that is worthy of consideration, but occasionally the choice must lie between those which offer the fewest objections. In making choice, therefore, it is a question of balancing these objections rather than of considering the benefits. The first and usually the determining factor is that of the cost per acre-foot, this cost being not far from $5 in the case of the ordinary successful irrigation reservoir. Next to the first cost is that of maintenance and depreciation, which in turn is determined by the probable life of the reservoir. As a rule the maintenance cost is very low excepting in case of earthen dams, where continual vigilance must be exercised and frequent small repairs to prevent defects developing.

The question of life of the reservoir or annual depreciation due to its gradual filling up with material washed from the sides is of great importance. A dam constructed in the course of main-drainage channel which receives all of the storm waters with accumulated gravels, sand, mud and debris, must hold behind it practically all of this solid matter. The clearer waters may be drawn down but in time this solid matter will accumulate, and in the course of decades reduce the capacity of the reservoir. On the other hand, if a similar dam is built on a side channel which does not habitually receive the waters from the great storms the reservoir may be filled by a large flood canal from the main stream and this flood canal may be manipulated in such a way as to receive the principal parts of the flood waters while rejecting and washing back into the main drainage all of the gravel and sand, and most of the mud.

Shallow and Deep Reservoirs.—There is sometimes opportunity for choice between two possible reservoir sites based upon the relative surface exposure as compared with the depth of water. The shallower one will first lose more water by evaporation because of the greater rapidity with which the water is heated by the sun, and second because of the larger area from which evaporation is taking place. Counterbalancing this, however, is the fact that the shallow reservoir is usually cheaper to construct, as it involves generally the building of a dam of less height.

Where the water supply is limited and must be conserved to the highest degree the deep reservoir possesses decided advantages over the shallow one on account of the smaller losses by evaporation. Especially is this true if the storage supply must be carried over from wet to dry years. In order to compare the merits of two reservoirs of about the same capacity, the one deep and the other shallow, it is necessary to determine the value of the extra water saved in the one case and compare it with the extra cost of construction. In doing this, due consideration should be given to future irrigation development and the probable rise in the value of a water supply.

CHAPTER XII

DAM SITES

General Conditions.—A feasible site for a storage dam is one where topographic conditions are such that the outlet from a large basin or valley may be permanently closed with a relatively small amount of material. The ideal site especially for a high dam is one where solid rock occurs in the bed and sides of a stream and where suitable material for building, preferably good rock, can be obtained in the immediate vicinity. Unfortunately good sites are extremely rare and often the skill of the engineer must be exercised in making use of localities not particularly favorable and in building with such materials as are most accessible. From the ideal conditions of a solid-rock foundation and a good quarry from which to obtain suitable rock for a dam, he must usually depart, and seek to make a safe structure upon a less firm foundation and from less suitable materials. Nearly ideal conditions are those shown in Plate XI, Fig. A, the site of the Roosevelt Dam, Arizona, before work was begun.

In some localities the depth to solid rock is so great that it is impracticable, if not impossible, to excavate to it for a foundation. Such a condition may entirely modify the type of dam to be used and even be a controlling feature in determining the height of dam that can be constructed. The fundamental questions concerning a dam site are (a) quantity of material required for a dam of given height; (b) material in foundation; (c) character of material available for construction; (d) conditions for spillway.

It is also sometimes necessary to consider the general location as to the practicability of delivering and installing the necessary plant and equipment for construction. It is not until the above questions have been answered by careful field examinations that the feasibility of any site can be established.

Surveys of Dam Site.—Having determined by general reconnaissance that a certain reservoir site is the best available for the storage of a given supply the next step is to select a site for a dam. As a rule there are several possible sites more or less contiguous to each other where a dam might be built, and there must be a balancing of the relative advantages and disadvantages of each. One location may require a little less cubical contents for the dam itself, but may require a deeper foundation. Another may be nearer the material suitable for construction, but require a greater cubical content. For each of these sites tentative plans should be made and careful estimates prepared in order to weigh their relative costs and merits.

The first steps in considering a given site is to prepare a careful topographic map of it. This map should be on a scale sufficiently large to permit quantities both for the dam itself and the foundation excavations being determined to a reasonable degree of accuracy. (See Fig. 38.) Ordinarily a scale of from 50 to 100 ft. to the inch and contour intervals of from 1 to 2 ft. are required. Topographic maps are not only valuable in preparing estimates, but also serve a useful purpose in the laying out of a construction plant and providing for the handling and storage of material.

The most economic and convenient method of making such survey is by means of a plane-table, as it is usually possible to cover the entire site from a few well-chosen stations and to sketch with great accuracy the topography of all salient points.

Foundation.—The determining factor after the consideration of the general location of a dam is the character of the foundation. Upon this may depend the height of dam which it is feasible to construct and the amount of storage capacity which may be made available. While it is relatively a quick and easy piece of work to make the topographic sketches showing surface features, it is not at all easy to ascertain the underground conditions which limit the character and cost of the structures. In general it may be said that the foundation is the most costly as well as the most vital point of a dam. Practically all failures come either through lack of knowledge of the foundation conditions or the neglect to take these conditions into account in planning the structure. The fundamental requirements of a foundation are stability or bearing power to carry the weight of the dam and water-tightness to resist percolation under the artificial structure.

The bearing power of a foundation determines to a great extent the character of structure which may be built. It must in every case be sufficient to carry the load imposed upon it without undue settlement. For high masonry dams a foundation is required which is practically unyielding for its load, since settlement especially under one part of the dam may produce stresses sufficient to rupture the masonry. For a low dam or one built of non-consolidated materials which require great thickness and width of base to sustain the water pressure less firm foundations may be used. For example a dam of loose rock and earth may be safely constructed upon a foundation of firm earth. In a structure of this kind a slight settlement in the foundation is taken care of by the large mass of non-consolidated material above gradually assuming a lower position. Here also it is necessary however, that unequal settlement of any considerable magnitude be avoided on account of the danger of opening fissures in the dam.

Water-tightness as applied to foundations is a relative term as all earth and most rocks are more or less porous to water under high pressures. But, hard, compact rock, without fissures may for practicable purposes, be considered as water-tight. In the most compact rock, however, seams or fissures are frequently found. Earth, especially that found in the bed of streams or old waterways, is likely to be made up of strata of varying character, some of which permit the passage of water through them. While the existence of a semi-porous material in a foundation may not be sufficient to prevent its use, it is of the highest importance that a knowledge be had of the character and location of such materials in order that suitable plans may be prepared.

Borings and Test Pits.—The most complete examination which it is practicable to make is really none too good in determining the character of foundation. There is little excuse for the engineer attempting to make plans for a dam without first obtaining full information concerning the conditions below the surface of the ground. The cost of such examinations, though large, is not prohibitory, and funds expended in this manner usually result in the greatest ultimate economy. For making such examinations there are commonly employed test pits, wash borings and core borings.

The simplest and most common method of making examinations in dry earth or indurated material is by means of ordinary test pits or open wells dug by hand. In all parts of the country are to be found laborers who have had experience or who can be quickly instructed in the matter of digging and shoring out the open hole. Such test pits afford access to the ground in a way which permits very thorough examination.

It frequently happens that the conditions are such that the ordinary open test pits cannot be economically utilized over the entire area. This is especially the case if the amount of water encountered is too great to be handled by ordinary pumps. It then becomes

FIG. A.—Storage dam site, Roosevelt Dam. Salt River Project, Ariz.

FIG. B.—Drilling for bed rock at storage dam site. Shoshone Project, Wyo.

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FIG. C.—Spillway of Bumping Lake dam. Yakima Project, Wash.

FIG. D.—Spillways of Roosevelt Dam. Salt River Project, Ariz.

necessary to procure some form of apparatus for more systematic work. Recourse is usually made to the ordinary well driller who, with suitable "rig" or outfit is accustomed to drilling wells through sand, gravel, boulders, and solid rock. He can usually determine with reasonable degree of accuracy the character and thickness of the different layers or strata, and if skillful can shut off the surface flood and ascertain whether the deeper strata are fissured and carry considerable amounts of water.

Great care must be observed in taking and studying the material brought up. The form of drill ordinarily employed shatters and pounds the rock into sand or powder and there is constant tendency for material dislodged from the upper part of the hole to fall down and become mixed with that which is being broken at the bottom. The material as it is brought up in a bailer is washed with water in such way that the finer particles are apt to be lost and the samples examined thus represent usually the harder portions of the rocks penetrated.

Where the foundation material consists of rock or indurated material, it is desirable to use some form of core bit for cutting rather than the chopping tool referred to above. There are various forms of core bit operated with a rotary motion, sometimes armed with diamonds or borts. These cut away an annular space, leave a central core which can be removed for study. The softer layers tend to disappear and care must be exercised in measuring the depth of the hole to account for any soft layer which may be passed through and so completely ground to powder as to be unrecognizable. If a continuous core can be had, this will furnish a fairly complete record of the rocks penetrated.

The cost of test pits and drill holes varies with the locality. This in turn governs largely the price of labor and material. In general it may be said that for ordinary test pits up to 20 or 30 ft. in depth, the cost per vertical foot is between $1 and $2. For the ordinary chopping bit where holes are put down to a depth of 50 or 100 ft., and aggregate possibly a thousand feet or more, the cost should be approximately the same. For the diamond or other core bit, the cost may be from $3 to $5 per vertical foot. A view of a diamond drill equipment mounted on a scow at the Shoshone dam site, Wyoming, is given in Plate XI, Fig. B.

The cost per foot is dependent largely upon the number of feet drilled in the same locality as one of the principal items of expense is procuring, moving and installing the apparatus. After it is once in place and in operation, the number of feet drilled may be increased at will and the cost per foot materially reduced.

The number of test pits or borings which must be made is, of course, dependent upon the material encountered and can rarely be determined in advance, if for example, a half dozen borings are made at fairly regular intervals across the proposed site and all show practically identical results, there is very little apparent need of increasing the number. If, however, each test pit or boring shows some different condition and gives rise to suspicion as to the safety of the foundation, then the number must be increased until the experienced engineer feels that he has a fairly complete knowledge of the conditions.

Character of Foundation.—The character of materials in a foundation are as diverse as are the components of the earth's crust. Passing beneath the surface cover of soil, if any, on the hill sides, and of clay, sand, and gravel of the river bottom, there is usually encountered a layer of disintegrated material, resulting from the weathering of the underlying rocks. These may be horizontal or partly inclined or even vertical. They may be shattered, faulty, or may be in thin shaley layers or in massive blocks. All of the essential facts concerning the material, its position, especially its permeability to water under pressure, should be thoroughly understood before the final plans are determined upon. The test pits or drill holes should be continued not merely into the firm rock but, depending upon the geologic structure, a few at least should be put down to a depth of 100 or more feet, to be certain as to the still lower strata. Especially is this necessary in a region of eruptive or crystalline rocks. For example, there are instances where dams have been built upon lava supposed to be of great thickness, but which ultimately proved to be a relatively thin shell, with clay underneath. In another case, plans were made for a very elaborate structure, when a deep drill-hole revealed the fact that the crystalline rock on which a part of the dam was founded was in reality a cliff overhanging a former pocket in the river bed and beneath this was an ancient river channel filled with gravel.

For high masonry dams where the loading on the foundation is heavy, the crushing strength of the rock should be determined, especially where the softer varieties of rock are encountered.

Character of Materials for Construction.—Having determined the character of materials composing the foundation, it is required next to ascertain what materials in the vicinity are best suited for building the dam.

Assuming that the foundation is of solid rock it is highly probable that other rock can be found in the vicinity suitable for some form of construction. If so, quarries should be opened by experienced men at the earliest practicable date to ascertain the character and size of stone which may be had. The actual opening of a quarry has sometimes revealed the existence of conditions which have necessitated an entire change in plans or methods of constructing the work. For example, as the Laguna Dam, on the Colorado River, Arizona-California, the outer shell of granite was firm and could be quarried into large blocks. From this it was assumed that the rock below the surface would be still better. The opening of the quarries, however, revealed the fact that the surface rock was the only fair material available.

If rock of large size, weighing a ton or more cannot be obtained economically, the next consideration is whether the material is suitable for being crushed and used in concrete. Where foundation conditions are unsuitable for a masonry structure, or where suitable rock for masonry cannot be obtained, consideration must be given to unconsolidated material. This requires a study of the problem of making a substantial and water-tight structure of loose rock, gravel and earth, or in some cases of earth alone. If an unconsolidated or loose structure is to be built, the vital point, so far as material is concerned, is to find a clay or combination of clay and sand or gravel which, when mixed in proper proportions, is practically impervious or water tight. Such a dam in effect consists merely of an impervious layer properly held and sustained in position, the remaining materials being simply for the purpose of protecting the water-tight portion of the dam.

In a timber country, especially where dams of a relatively temporary character are required, consideration must frequently be given to the use of wood and stone. The first question as regards material is to find trees of suitable size and quality of timber for supplying logs for building cribwork, and next to this is the obtaining of rock, preferably large stone, for filling the cribs and preventing their being washed away.

Accessibility of Materials for Construction.—Next in importance to foundation conditions and materials for construction is the accessibility of these materials to the site of the work. It is sometimes the case that the best materials for construction purposes are so located or are at such a distance from the dam site as to make the cost of transporting them almost prohibitive. It frequently becomes a question of judgment whether it is preferable to go to some distance from the work in order to obtain the most suitable material, or to attempt to make a safe structure from less favorable materials which are found in the immediate vicinity. In deciding this question consideration should be given first to the item of safety and second to that of cost.

In determining the cost of delivery of material to the dam, the conditions under which it must be excavated, length of haul, character of roads and methods of transportation must be considered, The magnitude of the work is also of prime importance in deciding what means of transportation it is feasible to employ. For example, a plant which would handle a million yards of material at a low unit cost might result in very high unit costs if used for one-half or one-fourth this amount. It consequently becomes a question of determining for each particular job the most economic methods of transportation.

Before it can be said that material is accessible to a given site at a reasonable cost the methods of transporting the material and the cost of the equipment required must be carefully determined. With a good foundation and with quarries located at a reasonable distance, it may be found advisable to build an earth- and rock-fill dam rather than attempt to haul stone from the quarry for a masonry structure.

Spillway.—Even of more immediate importance than the determination of the character of foundations and materials to be used in constructing the dam is the provision for the safety of the structure by having ample spillway capacity for the discharge of excess waters. This should be so planned and built that it cannot be obstructed by any probable accident, nor be closed readily even by deliberate act. It is the safety-valve which insures against loss of life and property and as such should not be a subject of any possible or probable closure.

The ideal situation for a spillway is at a point not immediately contiguous to the dam where the water can overflow in a broad sheet and be collected into a channel through which it may reach the river at a point sufficiently far below the dam so as not to disturb the foundations. In some situations it is impossible to find such a spot and the spillway must be built on the natural rock or soil as part of the dam itself, and here great precautions must be observed to hold the water in check and to absorb its energy of motion in such way as not to have it injure the structure.

A criticism which has been applicable to many of the dams built in the past has been that the spillways have not had sufficient capacity for the extraordinary floods. Provision has been made for the average high water, but the failure of some of these structures illustrates the fact that the great flood of the century is one which far exceeds the average high water and may occur immediately after an ordinary flood has filled all the basins and river channels. The fact that the reservoir frequently acts in such way as to absorb most of the flood water and does not permit any to escape tends to give a false sense of security, or the fact may be pointed out that water has never reached nor filled the existing spillway and therefore there is little to be feared that it ever will. This is the fallacy which has resulted directly or indirectly in many catastrophes. Succeeding structures have been built with small spillways because of the fact that dams already erected have not been threatened by the small capacity already provided. In this, the fact is ignored that the record of a few years or even of a decade or more is not to be relied upon for the extraordinary conditions or combinations which may occur and for which the spillway must be arranged.

The condition to be sought besides those of safe location and ample capacity is solid rock which can be built upon in such way as to form a long sill or weir over which the floods may pass. Usually if rock exists in the right location it is necessary to cut this down to the desired elevation. . Occasionally the quarries for supplying material for the dam can be located in the proposed spillway, as at Roosevelt, Arizona, (Plate XI, Fig. D) so as to make use of the material removed. If, however, the rock is already too low it may be brought up to a proper elevation by a low masonry dam forming thus a subsidary structure to the main work.

In some localities, for example, in a narrow canyon as at the Shoshone Dam in Wyoming, it has been necessary to cut a tunnel through which the floods may discharge. In this case, the overflow sill is constructed on a curve at the head of the tunnel, thus forming a broad funnel approach in which the water may be gathered.

Occasionally a spillway must be over earth or gravel or partly indurated materials which are easily worn away by water. In such cases ample protection must be provided by structures preferably of concrete or masonry and the water which passes over the spillway must be collected in a channel protected from backcutting by being lined with concrete or timber (Plate XI, Fig. C). Provisions must also be made by means of chutes or drops by which the water will expend its energy internally or against some indestructible material. Timber has occasionally been used in connection with spillways, but the disadvantage is that, as these spillways receive water perhaps at intervals of many months or once a year or longer, the wood is dried out, warps, or decays, so that when brought into use suddenly the structure may fail. For this reason, as above stated, concrete or masonry is most generally employed.

Records of Stream Flow.—In considering the size of spillway, it is necessary to have records of stream flow not only giving the total amount but even more important, the details of behavior of individual floods. It may be assumed that as far as the spillway is concerned the flow through the greater part of the year is insignificant, as it is stored in the reservoir, but the critical points are on the probable behavior of the stream at extreme high water. It is particularly important to know the intensity of the flood or the amount of water delivered at short intervals during the height of the flood. Assumptions must be made, based upon a full reservoir, with a flood coming from the entire drainage basin. If this basin is heavily wooded or covered with a thick growth of bushes and grass, the rate at which the flood will reach the reservoir and consequently must be discharged over the spillway may be assumed as relatively small. If, on the contrary, the drainage basin consists largely of rock and uncovered soil, or is traversed by roads and paths, which in time of storm act as collecting drains, then the rate at which the water will reach the reservoir is greatly increased and hence the probability of need of providing a large overflow.

Consulting the rainfall records, it is seen that a rate of 1 in. per hour for the entire basin is extremely heavy, although as high as 3 in. per hour have been known in tropical countries. If the drainage basin consists of 12,000 acres, this would mean 1,000 acre-feet occurring in an hour or at the rate of 500 second-feet continued through twenty-four hours.

In other words, assuming that all of the water on this drainage basin will reach the reservoir within a day a spillway of at least 500 second-feet must be provided. As a matter of fact, however, much of this water might reach the reservoir in a shorter time and the spillway must be correspondingly increased.

A large factor of safety must always be employed so that after estimating the largest probable flood, it is the part of wisdom to multiply this by two at least, sometimes by a larger factor, if the records of rainfall or river flow have not been extended over several decades.

Kind of Dam Best Adapted to Suit Conditions.—From what has been stated above, it is evident that the kind of dam must be determined by the conditions already discussed of foundation and materials available. Plans may also be modified in accordance with the funds which are at hand and the prospective returns from the investment. If the foundations are good, that is, of solid rock and quarries of suitable rock are available, a masonry structure may in general be considered as the best, but something cheaper may be allowable if the financial ability of the builders will not permit the better structure. The great danger in this connection lies in attempting to reduce the cost below reasonable limits of safety.

Having determined upon the most economic type of dam and then having modified this to suit financial requirements and brought it to a minimum of safety under the direction of an experienced and competent engineer there is sometimes a tendency to practise a false economy in the character of work and quality of materials used in construction. In some cases the work is entrusted to a builder, who in his desire to lessen the cost reduces the dimensions of the dam and still further cuts down the factor of safety. This has been the cause of several failures; the plans were modified by experienced men to a point where they could no longer permit further reductions of cost and then the work was entrusted to men who still further cut down the requirements, not letting it be known, however, that the approved plans were being changed in detail. These changes were not discovered until after some catastrophe had occurred and the question was raised as to whether the dam had been correctly designed or a proper type of structure adopted.

CHAPTER XIII

TIMBER DAMS

Kinds of Dams.—A dam is an obstruction placed across a stream or depression and so devised as to hold back or obstruct the flow of the water. It may be built in such way that water will flow over it, in which case it is termed an overflow or submerged dam or weir; or it may be of such height that it cannot be overtopped. In the latter case, if relatively long and low, it may be termed a dike or levee.

The essential feature of any dam is the relatively impervious layer, curtain or blanket held in place by a suitable arrangement of material. The whole structure may be impervious or only a thin section of it either in the interior or against the upper or water face. The material which holds this impervious layer in place may be of wood such as logs or of earth properly compacted, of stone either loose, or carefully laid, of concrete, brick, steel, or almost any other building material.

This material may be arranged simply as a great mass dumped in together or may be carefully proportioned and built to secure the greatest economy of material, following the rules laid down by scientific observation of the strength of materials and deductions based upon mathematical principles.

Dams are classified according to the material of construction and its arrangement in the structure. One form grades by insensible degrees into another, but the following may be distinguished:

Timber dams, including brush dams and log or crib dams.
Earth dams.
Rock-fill dams.
Rock and earth-fill dams.
Masonry dams.

Early Stages of Development.—The most elementary form of dam, so far as known, is that constructed by the beavers or their relatives. Examples of the work of these animals are to be found in various sections of the country and the rude skill displayed by them in using timber and earth and stone to form an obstruction for holding up small heads of water causes us to question whether it is not from them that man learned his first lesson in this branch of engineering.

The early dams built by men were constructed of small logs and brush, and, like the beaver dams, were arranged in such a way as to have the branches interlaced so as to form a more or less systematically interwoven mat or rude fence. Man learned to improve upon these methods by holding the light material in place, and prevent its being floated away by means of loose rock. Larger logs were also soon used, these being arranged more and more regularly until by degrees there was an evolution from the irregular brush and stone dam to the systematical dam in which the logs are arranged in geometrical forms with the spaces between filled with carefully placed rocks, both large and small.

In the earlier stages of irrigation the brush and stone dam was largely used for diverting water from the stream into the canal as shown in Plate XII, Fig. A. For the small irrigation systems where each canal supplied water to but a few farms, it was by far the most economic structure that could be used. At high water it was usually wholly or in part washed away, but this did not result in any noticeable loss. After the stream subsided in summer so that the water no longer flowed freely into the head of the canal, the farmers assembled, cut the necessary brushes from the adjacent banks of the stream, floated these into position and secured the mat thus made by placing boulders and small stone upon it. In plan, the dam was usually placed diagonally up-stream from the intake of the canal so as to force the current directly toward it.

Improvements on this rude form were later made by tying the brush together with wire and anchoring it to posts. As the water still further subsided, the dam was made more nearly water tight by throwing gravel, sand and earth against its upper side. The total outlay of time and labor required for this work was not usually great and the annual cost of replacement less than the interest and depreciation on a more permanent structure.

After crop production and land value increased a point was reached when it was not economy to repair these dams annually, or after each flood, and consideration was given to a more permanent form of structure, one which did not necessitate men leaving their farms at the critical time of crop seasons for the purpose of making repairs. It also frequently happened that the inlet of the canal was at such a height above the bed of the stream that the brush dam was not sufficient to force the low water flow up to it. In that case, a structure was required which would raise the water and which would be strong enough to resist the floods. The next step was therefore the consideration of a dam built of more substantial materials. It is thus seen that the timber dam is, to a certain extent, the outgrowth of more systematic arrangement of the same class of material used in the brush and stone dam. One of the intermediate types of dam is shown in Plate XII, Fig. B.

Use of Timber Dams.—In regions where timber is plentiful and consequently cheap, timber or timber and stone dams are extensively used. As a rule this use is confined to diversion wiers or submerged obstructions the water flowing over them at all times when there is a sufficient supply in the stream. In some cases timber dams are also used for storage reservoirs where comparatively low heads are required.

Where wood is exposed to both wet and dry conditions, its tendency to decay is rapid. For this reason timber dams used in streams which are dry during a portion of the year, or where there is a wide variation of head against them must be considered as temporary in character. The conditions which will justify the construction of a temporary structure of this kind will vary in each particular case and locality.

Where Timber Dams are Applicable.—Timber dams are applicable for practically all conditions where a low head (20 ft. or less) is required and where there are suitable materials available at reasonable cost for their construction. The principal materials required are logs, either rough or sawed into square timbers or planks, and stone varying in size up to 200 lb., or even more. They are especially adapted to regions where trees of suitable size and quality for logs can be cut on the upper reaches of the stream and floated into position.

Timber dams may be adapted to practically any kind of foundation conditions, from solid rock to comparatively soft earth, by giving them sufficient width of base and using cut-off walls where required to avoid percolation under the dam. Except on solid-rock foundation, it is necessary also to protect the lower toe from erosion and undermining the structure. If properly constructed their safety is not endangered by slight settlements, and for this reason the timber dam may be constructed on a foundation which would be unsuitable for a less elastic structure, such, for example, as masonry. (See Plate XII, Figs. A and B.)

The plan of the dam may be straight or curved, and built at right angles to the current or diagonally with it. The latter plan

FIG. A.—Brush and stone dam, typical of pioneer conditions. Las Cruces canal, Rio Grande, N. Mex.

FIG. B.—Log and earth dam. Cimarron River, N. Mex.

FIG. C.—Foundations for timber dam. Yakima Project, Wash.

FIG. D.—Apron of partly finished timber dam. Yakima Project, Wash.

is sometimes used in order to increase the length of overflow and decrease the depth of water on the crest. In this case there is a tendency, however, to force the stream toward one bank, with consequent danger of erosion, or if directed toward the intake of the canal, with liability of throwing the floods into the head and bringing in large quantities of sand, gravel and débris.

A curved plan of timber dam has occasionally been used in order to gain the advantage of the effect of the arch. The water pressure against the up-stream face putting the structure in compression. The gain in this respect is not very great, but is worthy of consideration if the abutments are sufficiently firm.

Conditions of Stability.—Unlike a masonry, concrete or similar rigid structure, a timber dam is not dependent for stability on each part being held by friction or by the resistance due to cohesion of the various parts. On the contrary, it is essentially a wooden frame tied together in such a way as to be moderately elastic and held from floating or sliding by its loading of rock, which in turn is held in place by the network of timbers. This sort of structure allows a certain amount of settlement or sliding and an adjustment under pressure of gravity so that a change in position which might be fatal to almost any other form of dam may tend to strengthen rather than weaken the structure.

Timber dams are sometimes also built with such an up-stream slope that the weight or downward pressure of the water tends to hold them firmly on the foundation so that the added weight of water with increased head tends to strengthen the factor of safety against sliding.

The principal features to be safeguarded in the construction of timber dams are:

(a) Protection against sliding on the foundation.

(b) Bonding together of the various timber elements.

(c) Protection against undermining.

Sliding on the foundation, as heretofore mentioned, is provided against by weighting the structure by means of heavy rock, and in some cases also by constructing the up-stream slope at such an angle that the weight of the water exerts a vertical component through the dam on its foundation. The holding of the dam together may be accomplished by means of drift bolts driven through the various timbers so as to securely tie them together at each point of junction.

The dam may be protected against undermining, if it be on other than solid-rock foundation, by carrying an apron for some distance down-stream below the lower tow. It is necessary also to give protection against cutting around the abutments by constructing the dam well into the banks or providing masonry abutments against which it may rest.

Additional strength is sometimes given to timber dams by constructing them either in the form of an arch or "V" shape. Dams built in this form must have solid banks against which the ends may rest, or masonry bulkheads should be constructed. If artificial abutments are used, they should be carried up above the flood line of the stream.

Water-tightness.—Timber dams are made water-tight, or nearly so, by means of a tight facing of either earth and gravel or of wood. This water-tight facing should be located at the up-stream face of the dam. In general, it is believed that a water-tight facing of earth and gravel is superior to that of lumber on account of its greater lasting qualities, and also its tendency to remain tight under low-water conditions.

The interior spaces of the dam should be filled with loose rock and where available, gravel should be carefully packed around the various timber members in order to further protect them from decay. The interior of the dam should be sufficiently porous that water which may find its way through the water-tight face will be quickly drained away.

Types of Timber Dams.—Various types of timber dams have been successfully used and it is impossible to say that any one type is superior to another. Each particular design should be made to suit local conditions of foundation and material available for construction, for example, in a locality remote from mills, a design adapted to the use of round logs would be probably more economical than one of sawed timbers, even though the amount of material required in the former case was greater than in the latter. On the other hand, in a locality where timber is less plentiful and where dimension lumber can readily be gotten, a saving might be effected by using sawed timbers and so designing the structure as to require the minimum amount.

Practically all of the different types of timber dams depend upon the principles heretofore given for stability and water-tightness.

Among the more common types of timber dam which may be mentioned are log and brush dams, crib dams, combination crib and pile dams, and framed dams.

Log and Brush Dams.—This type of dam is well suited to localities where timber, preferably long trees, can be obtained without difficulty. It consists essentially of a series of mats of logs of various lengths laid in the stream parallel with the current. The tops of the trees in each case being placed up-stream. At the lower face of the dam the various layers of mats are separated by means of one or more rows of fairly uniform sized logs carried crosswise. This has the effect of building up the lower portion of the dam more rapidly than that portion further up-stream, and giving a long flat slope to the upper face as shown on Plate XII, Fig. B. The horizontal and longitudinal timbers which form the lower face of the dam should be securely fastened together by means of drift bolts, or otherwise.

In a dam of this kind a thin layer of gravel and fine brush should be placed between the various courses of the timbers and the structure should be given weight and stability, as well as water-tightness by covering the up-stream face with earth, loose rock and gravel.

It is well to allow the first two or three courses of timbers to project some distance down-stream below the toe of the main dam, thus forming an apron for protection against erosion. For a dam of moderate height, say from 8 to 10 ft., the first, or bottom layer of timbers should project down-stream from 20 to 30 ft., the second layer from 10 to 15 ft. and the third layer from 5 to 8 ft.

Crib Dams.—This form of dam consists essentially of a series of timber cribs built up across the stream and filled with loose rock to prevent their being washed away. These cribs are commonly built of either round or sawn timbers. They may also be built of various shapes and sizes, depending upon the material available and the height of dam required. (See Plate XII, Figs. C and D.)

A common form of crib dam consists of a series of rectangular cribs from 10 to 15 ft. square carried in a straight line across the stream. Where the foundation is of solid rock it is a common practice to excavate into the rock sufficient to receive the first row or timbers. The first or second layer of timbers from the foundation are usually laid close together so as to form a floor in each of the cribs for holding the rock. The timbers are all securely fastened to each other at their junctions by means of drift bolts or pins. Water-tightness is secured by means of a facing of gravel and earth, or sometimes of planking.

An apron for protecting the lower toe of the dam in case of floods is frequently made by constructing a second row of low cribs below the main dam and filling them with rock.

In other forms of dams the cribs, instead of being built up verti-

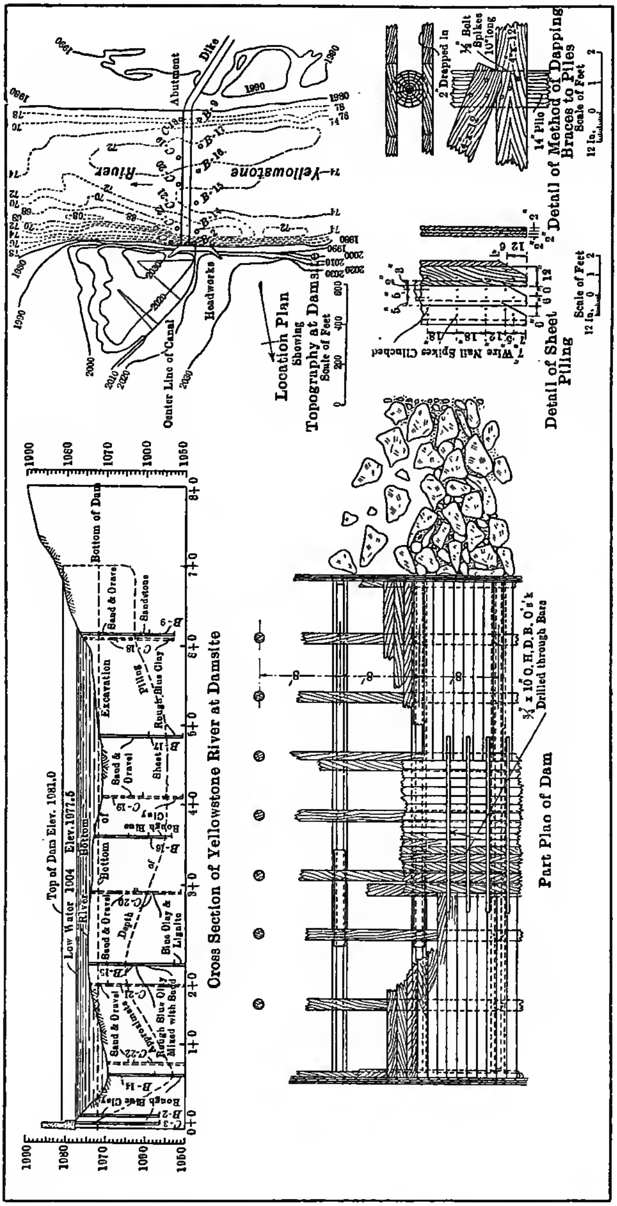


FIG. 39.—Timber and rock dam on Yellowstone River for Lower Yellowstone Project, Montana.

cally, are inclined on the up-stream or down-stream face or both, thus giving a triangular section. A crib with the inclined face up-stream has the advantage of utilizing the downward pressure of the water in producing a greater degree of stability. Also, one with an inclined down-stream face tends to carry the overflow in time of floods away in a more nearly horizontal direction and with less liability of erosion at the toe than is the case when the fall is vertical.

Crib and Pile Dams.—A common form of dam and one adapted to a soft bottom, which does not contain quicksand, is the combination of driving piles and against these building the crib work.

Two or more rows of piles are driven directly across the river at right angles to the current. The cribs are then constructed between the rows of piling and filled with rock or rock and brush. As an illustration of this type of dam, is that on Yellowstone River, Montana, below Glendive, a part plan of which is given in Fig. 39, together with location, plan and cross-section of the river.

In Fig. 40 is given the cross-section of the dam showing the relative position of the piles and the braces, with apron and protecting rock below.

A modification of this form is to drive a double row of piles across the stream with a

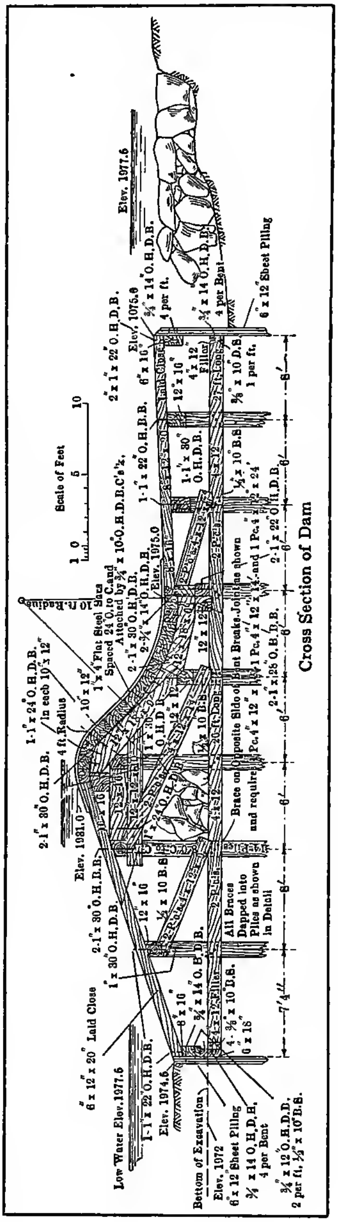


FIG. 40.—Section of timber and rock dam on Yellowstone River, for Lower Yellowstone Project, Montana.

clear space of about 2 ft. between them. The piles in each row are placed immediately above and below each other and spaced the same distance apart as the two rows are distant from each other. These spaces between the piles are then filled with logs built up crib fashion and laid at right angles to each other. The logs parallel to the direction of the current are allowed to project some distance up-stream so as to form the upper face of the dam, and terminating on the lower side just below the lower row of piling. Care must be taken in driving the piles so as not to permit the river to scour out the bottom between them, and thus permit a current to get started under the crib work. Protection of the bottom during the driving of the piles and construction of the dam may in some cases be secured by means of brush mattresses. Where this cannot be done it is sometimes advisable to first float the cribs into position and then drive the piles through the cribs, the latter serving to protect the bottom from erosion.

Framed Dams.—The frame type of dam requires far less timber than the ordinary log or crib dams heretofore described. For this reason it is better adapted to localities where timber is scarce. For convenience in framing the timber should be sawed to regular dimensions.

The dam consists essentially of framed timber bents placed parallel with the current. The bottom timbers of the bents are fastened to cross sills set into the foundation and securely anchored. Where the foundation is on rock the anchorage may be made by means of iron bolts split at the lower end and wedged into holes drilled in the rock.

The upper face of the dam should be inclined at an angle sufficient that the vertical component of the water load will act as a weight to prevent sliding.

Water-tightness is ordinarily secured by means of a plank face on the upper slope of the dam. The interior spaces between the bents are in general filled with loose rock to give the structure greater stability, although this is not absolutely necessary, safety being insured by the strength of the bents and the water load on the flat upper face.

The lower toe should be protected by means of an apron carried well down-stream. The lower end of this apron should be further protected by means of piling or rock. The force of the water may also be broken by constructing the lower face of the dam in steps or on an incline.

A layer of loose rock or earth and gravel should be placed on the upper face of the dam for some distance above the toe or in place of this a mass of concrete making a more permanent structure as shown in Fig. 41.

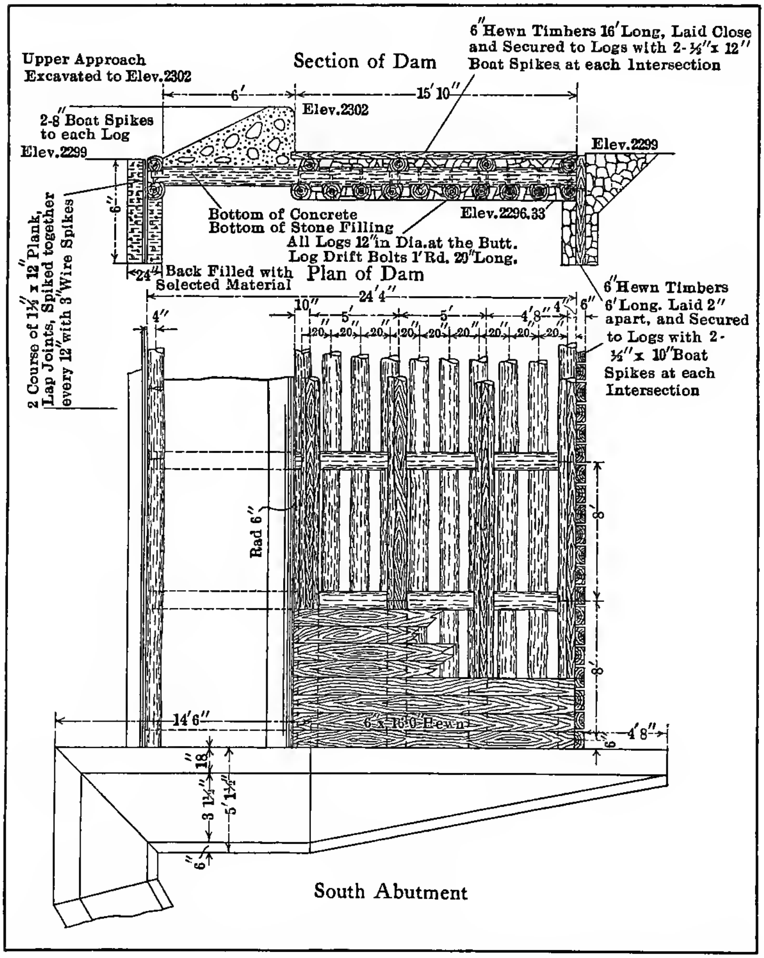


FIG. 41.—Concrete, rock and timber diversion dam, Yakima Project, Washington.

Limits of Height.—The height to which timber dams may be built is limited largely by the character of the foundation and quality of material available. There are examples of timber dams with heights of from 30 to 40 ft., or even greater, which have stood for years. On a firm rock bed not easily eroded and with heavy long logs and large stone there is no reason why even these heights should not be exceeded.

Ordinarily the use of timber dams is limited to low heads, generally not exceeding 15 or 20 ft. For such heads cribs may be built of logs or planks floated into position if the water is sufficiently deep, loaded with rocks and the work carried on with a reasonable degree of safety. For higher structures a greater degree of protection in their building is necessary.

On account of the temporary character and the possibility of failure after a few years of service, timber dams cannot be strongly recommended for high heads or for localities where any large quantity of water is to be held in storage. For diversion weirs and low dams, especially in localities where timber is cheap they frequently are the most economic form of dam that can be adopted.

CHAPTER XIV

EARTH DAMS

Site for Earth Dam.—The site usually chosen for an earth dam is of such a character that the building of a masonry structure upon it is impracticable. Frequently solid rock foundation conditions do not exist, or even where such conditions do exist suitable materials for the building of a masonry dam may not be available in the immediate vicinity. A firm rock foundation is as desirable for ar earth dam as it is for any other type. It is, however, possible to build an earth dam upon unconsolidated materials such as are usually found in river valleys and consisting of clays, sands and gravels with occasional boulders. It is also possible to use for the body of an earth dam materials that are commonly found convenient to any site which may be selected.

On account of the conditions above stated possible sites for earth dams are far more common than those suitable for masonry structures. It is not to be assumed, however, that all possible sites are equally satisfactory, or that any which can be found in a particular locality are ideal. The choice of a site is frequently a matter of compromise between alternatives any one of which may be made to serve the purpose but none of which are particularly attractive. It is usually possible to find points of criticism for every site as well as for the type of structure best suited to it. The choice is therefore not between locations offering superior advantages but rather between those possessing disadvantages which should be avoided.

Foundation.—One of the principal requirements for the foundation of an earth dam is that it shall be practically water tight below the lower point of the structure. It is essential also that the material be firm enough to sustain the load which is imposed upon it. The latter condition is less likely to give trouble than the former, and there is probably no one question of more importance in connection with earth dams than that of the water-tightness of the material upon which they are built.

As a rule the surface and sub-surface materials have been laid down by running water which results in their being stratified or consisting of alternate layers of clay, sand or gravel of various degrees of coarseness. These layers of pervious materials may consist of small horizontal courses entirely sealed within a thick impervious clay stratum. Or they may extend for several hundred or even a thousand feet and terminate in some open channel or near the surface of the ground below. Water entering one of these sheets or layers of gravel may percolate slowly through it and escape at lower or more pervious points. Where such conditions exist it is essential that they be known and that provisions be made to prevent water in any quantity percolating under the dam.

Occasionally, the foundation consists of rock disintegrated in place and which has not been rearranged by flowing waters. In this case, there is no definite sorting of the sub-surface material, but this is often loose or porous, because of the solution and removal of the more soluble particles of rock, thus water may pass freely through it or along the old bedding planes. Under other conditions the foundations may be partly filled with material which has rolled in from the sides, such as boulders and smaller débris, the latter partly rearranged by the occasional floods but still quite pervious to water. Too great care cannot be urged in determining the character of the foundation materials especially under high dams. Where these are porous or otherwise unsatisfactory precautionary measures sufficient to insure the safety of the structure must be taken.

Selection Of Materials.—The materials to be used in an earth dam are governed largely by the character of those found in its immediate vicinity. It is usually not practicable to bring the earth for large structures from long distances excepting possibly a small amount of clay or other impervious substance. The selection of materials for a dam is therefore usually confined to a choice from one or two localities frequently where the formation is not ideal. The location of suitable earth for forming a water-tight embankment may govern to some extent the selection of the site for a dam.

The first and prime requisite for the filling for an earth dam is water-tightness and next to this stability. Finely divided substances such as silts and clays are the most nearly water tight, but frequently do not possess the necessary qualities for being compacted into a firm embankment. Gravel containing a small amount of fine material is capable of being so compacted but does not possess the requisite quality of water-tightness. The ideal combination is one composed of gravel, sand and finely divided earth such as silt or clay in such proportions as to make a stable yet impermeable mixture. To meet this requirement the spaces between the larger particles must be filled and the volume of voids reduced to a minimum, and yet with the component particles of such size that they will not slide freely upon each other.

Occasionally, though rarely, this combination is found in nature, but more often it is necessary to combine materials taken from different localities. In order to do this it is necessary to make a mechanical analysis of those available and combine them in the proper proportions to obtain the desired results. Where such mechanical mixtures are necessary constant vigilance must be exercised during the progress of the work in order to have at all times the proper combination. This is especially true for the impervious or up-stream portion of the dam.

Section of Dam.—The top width and external slopes, or cross-section of an earth dam is governed by somewhat arbitrary rules based upon experience in structures which have stood the test of time. On acount of the varying conditions of saturation and friction in different materials, there is no known law by which the resistance of an earth dam can be computed. As a rule, the slope on the up-stream or water face is made less steep than that on the down-stream or dry side, because of the fact that the saturation leads to a tendency to slide or slough, especially when the water is being drawn down in the reservoir.

For the upper or wetted slope the minimum is about three horizontal to one vertical, although there are cases where a less slope has been chosen when this could be drained and protected by a suitable covering or by a paving of heavy rock. Dams have been constructed with an up-stream slope of 5 to 1 although 3 1/2 or 4 to 1 is as flat as are commonly used.

For the lower face, the minimum slope is usually 2 or 2 1/2 to 1. Occasionally, this is broken by horizontal berms or benches which serve to break the smooth face, give greater thickness to the base, provide convenient location for surface drains, and for roadways affording access to various parts of the structures.

The top width is rarely made less than 10 ft. for low structures say up to 30 ft. in height and for dams over this height is ranges from 10 to 30 ft., 20 ft. being the width commonly used.

Prevention of Seepage under Dam.—The points where the artificial structure joins or is placed upon the original earth or rock are those to which most care should be given as along this line of contact water under pressure usually finds most ready access and passage. Great percautions must therefore be taken in preparing the foundations and in arranging a junction such as to prevent or reduce the amount of seepage along this plane. Such seepage is checked or prevented usually by providing a cut-off trench or wall, extending deep into the foundations, this being extended or sometimes replaced by one or more rows of sheet piling driven as deep as practicable.

The ground to be occupied by the dam should be carefully cleaned of all stumps, roots or other organic matter liable to decay and all of the loose soil removed down to a depth of a foot or more beneath the surface, this depth being dependent upon the character of the ground. If the sub-soil is firm and free from roots or holes of burrowing animals, the depth of the stripping may be reduced but in general it is better to be on the safe side, and uncover the entire proposed base of the dam to a depth below where the soil shows the effects of penetration by roots and of weathering.

The material stripped off, if containing a loam, should be placed at one side out of the way for use later on the outer slope of the dam. Any clay, sand or other materials of good quality should be similarly disposed of to be utilized later by being incorporated in the body of the structure.

Placing of Materials in the Dam.—There are in use many different methods of placing materials in the dam, namely, by teams and scrapers, by wagons hauled by horses or traction engines, by railroad cars, by cableways, by mechanical conveyors or by the action of water itself in the hydraulic processes. Selection of the particular method to be used is dependent upon the size of the structure, the location of the materials to be moved, and other conditions. For a small dam it may be impracticable to provide an expensive system of traction, while for a large structure an elaborate preliminary equipment may result in the greatest final economy.

The simplest method of loosening and moving dirt and one which is generally used in the construction of small earth dams is by plow and drag, slip or wheel scraper. Suitable material found in the vicinity, is loosened by blasting if necessary, plowed up and then hauled into place by the scrapers. Skill and care are necessary in depositing the material in such way that it will be thoroughly trampled by the horses. It should be kept sufficiently moist to compact readily, and if not well trampled by the men and horses, the earth should be further compacted by systematic rolling.

In depositing the earth or other material, it should be spread out in thin layers and not allowed to accumulate in small piles. These layers should average not more than 6 to 8 in. in thickness and be

FIG. A.—Foundations for earth dam, showing excavation for puddled core and earth being brought to the site by railroad train, then distributed and rolled in thin layers. Umatilla Project, Ore.

FIG. B.—Earth dam partly protected by heavy gravel on water side. Boise Project, Idaho.

(Facing Page 214)

FIG. C.—Hydraulic construction of earth dam, giant in foreground washing earth and small rocks into flumes supported on trestles and conveying materials to site of dam. Okanogan Project, Wash.

FIG. D.—Completed dam built by hydraulic process, shown above.

kept wetted by hose or other means to a degree sufficient to give the most dense mass possible when compacted.

Where large quantities of material are to be handled and especially where the borrow pits are located at some considerable distance such as half a mile or more, it is necessary to provide more economical and quicker modes of conveyance than by horses and scrapers or carts. In such cases, small construction railroads are generally used and trains of from five to ten cars, each holding from 2 to 3 yd. of earth or more, are employed. (See Plate XIII, Fig. A.) The earth is usually excavated by steam shovel or similar device, and the cars carry it upon the embankment or upon a trestle adjacent to it. The economy of this method of conveying earth is dependent largely upon the arrangement of the tracks, so that the steam shovel and trains will move in unison and there will always be ready a train to receive the earth from the shovel and at the same time this train will not be delayed in getting its load. In place of the train it is occasionally economical to use dump wagons drawn by horses, these being organized in a way similar to that in the handling of trains, the wagons following a certain route, so as to come under the shovel at proper intervals without delay.

The earth dumped from the side of the trains or wagons must be spread and rolled by some suitable means. This spreading and compacting is usually accomplished by drag scrapers and by horse or steam roller, or similar device. In arranging the trestles for delivering the earth by train at the site of the dam, they should be so planned as not to come within the structure itself. In a few instances, large earth dams have been built by simply side dumping from parallel trestles, as is occasionally done in building large railroad fills. This leaves the timbers embedded in the body of the embankment which is allowable in a railroad fill or to a small extent in an earth dam yet the decaying wood may become a source of danger. The embedded timbers if large in aggregate bulk prevent the earth from settling uniformly and there are apt to be spaces along the timbers where the water can find its way and as these rot away the settling becomes unequal and there is liability of leakage or failure of the dam.

Placing of Materials by Hydraulic Method.—The building of a dam of earth and small rock by hydraulic methods consists essentially of the process of dislodging the material by means of a stream of water undercutting and washing it down, collecting the mud-laden stream in suitable flumes and keeping this stream moving at relatively high velocity so that it will not deposit the material which it is carrying until the point is reached where it is desired to leave it.

In order that this process of moving and depositing earth may be economically carried on, it is necessary to have, first, a small continuous flow of water under sufficient head, say 100 ft. or more, so as to have under control a powerful stream which can be directed against the unconsolidated materials, such as clay, sand and gravel, to be moved; second, these materials for economical construction should be at an elevation sufficiently above the location of the proposed dam so that the muddy water will flow by gravity to the point where the materials are to be deposited although they may be lifted by centrifugal pumps; third, the earth or small rock in the bank or pits to be used must be composed of large and small particles, such that when placed these may be mingled to form an impervious mass or core within the body of the dam. If these and other less essential conditions are easily fulfilled it may be practicable to move the material into place at a cost far less than by other means.

This process of hydraulic sluicing is an outgrowth of the experience of the hydraulic miners of California in washing gold-bearing gravels from ancient river beds. The water for washing is collected in small mountain reservoirs or conducted from a perennial mountain stream by flumes or small canals to a point as near as possible above the bank to be washed. Here it is turned into a pipe or penstock which terminates in a flexible hose with nozzles designed to give a high velocity to the stream. The arrangement of the nozzles and accessory parts for controlling it is known as a hydraulic giant. The giant is so mounted that it can be handled by one or two men, the stream being allowed to play against the bank and moved up and down or swung from side to side in accordance with the judgment of the operator.

The water striking the bank tears out the lighter portions and undermines the more solid parts. It carries in suspension the smaller particles and rolls along stones up to a weight of 100 lb., or even more. As soon as possible after leaving the foot of the bank the stream is conducted into wooden flumes, the process being assisted by one or more men using long-handled shovels or forks to keep the water and stones moving along and remove obstacles which collect in the stream, as shown on Plate XIII, Fig. C.

The slope of the flumes must be carefully adjusted to maintain a velocity sufficient to keep the material from being deposited. They are continued on trestles out to the site of the dam and branches are provided commanding the entire foundation. Gates or openings in the sides of these flumes are provided at the necessary points for discharging the water near the upper and lower faces where the larger stones are needed. From these points the smaller stones and fine material are carried inward toward the center of the dam. Along the axis of the dam the muddy water is held temporarily in a small pond in which the finer sediment is deposited thus forming a water-tight core.

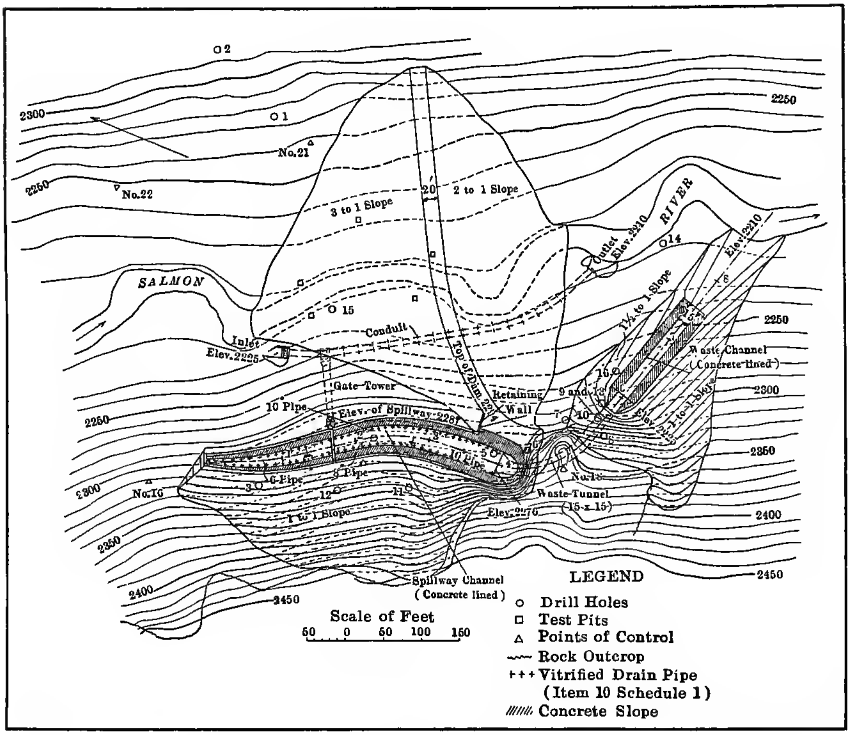


FIG. 42.—General plan of Conconully Dam, showing location of spillway and outlet works, Okanogan Project, Washington.

As a result of careful manipulation of the flumes the large rocks are deposited on the outside of the dam, the smaller stones and gravel inside of this and the finest sand and silt in the center or near the up-stream face. To bring about this result the flumes are shifted inward on the dam as the structure increases in height; finally a single flume deposits the last of the material on the crest, resulting in a symmetrical structure as shown on Plate XIII, Fig. D. The general plan of the particular work shown in this plate is given in Fig. 42, this being the Conconully dam across Salmon River furnishing water for the Okanogan Project, Wash. The area from which the material has been taken by sluicing is shown on the hillside in the lower part of the drawing, being nearly adjacent to the site of the dam.

Among the objections to the hydraulic method of constructing earth dams are those which arise from the limitations imposed by the quantity of water available for sluicing the material, and the difficulty of elevating this or bringing it to the required height above the dam to be built. In other words, there is usually not sufficient elasticity in the limiting condition to meet all of the requirements, for example, it may be discovered after the work is well opened up, that the best material to be utilized for the dam is located a little too low to be effectively washed or the position of attack must be changed, necessitating a reconstruction of the conveying flume.

A more serious objection is that arising from the tendency of material handled in this way to be sorted or stratified, for example, if the work is not carefully managed, it may happen that for a brief period sand may be washed into the dam and, due to the action of the water, deposited as a thin layer. The finer particles or mud will not penetrate this layer of sand and thus there is formed a line of stratification or thin layers of different degrees of fineness, offering opportunity for percolation or for sliding of one portion of the dam. Another objection lies in the fact that if there is an undue proportion of fine clay in the center of the dam, this will not deliver its excess water, except with great slowness, and remains a mass of unconsolidated material liable to behave as a semi-fluid.

The principal benefit claimed for this method is the relatively low cost of moving the material. When the conditions are favorable, it is remarkably cheap, far less than the ordinary procedure by means of plow, scraper, or hauling, but, as before stated, does not have the adaptability of the latter. Some extraordinarily low figures have been given of the actual cost of less than 5 cents per yard, but this is where great quantities have been moved with a very conveniently located bank of earth and with ample water supply. Under ordinary conditions the cost is higher and for most localities the conditions are so unfavorable that the cost is prohibitive.

Compacting the Material.—The proper compacting of the material in an earth dam is one of the most important details of construction. It may be done by simple or crude means. On smaller earth dams built by hand labor or by plow and scraper the earth can usually be compacted sufficiently by the trampling of men and animals. In some cases, the dam has been enclosed with a suitable fence and animals, bands of sheep, goats, range cattle, or horses have been driven backward and forward over the area.

A more systematic procedure is to utilize a roller drawn by horses or driven by steam or gasoline engine. The surface of the roller is usually corrugated, or the roller may be made of rings moving loosely upon an axle, so that each ring acts as an independent wheel, settling into the inequalities of the surface. A smooth roller is objectionable as tending to form distinct planes through which water may seep. While the surface is being compacted it should be kept moist.

Ramming by hand or by machinery is sometimes practised, especially over small areas, particularly where a closure of an earth dam is being made in a gap in the structure. Here, especial attention must be given to thoroughly compacting the earth and to the details of forming a close bond with the adjacent slopes. Light steam hammers have been utilized for rapid work in such confined spaces to secure quick results.

Prevention of Seepage through the Dam.—The making of an impervious wall or layer in an earth dam is a prime requisite. It is relatively easy to put enough material in place to hold back the water and to prevent the structure being washed away, but it is far more difficult to arrange this material so that water cannot find its way through minute channels or along contact planes. Primarily, seepage is prevented by a proper selection and mixing of materials and by compacting them thoroughly when deposited. There are, however, a number of devices for securing impermeability, each of these being used to greater or less extent, in accordance with the surrounding conditions and especially the character of material available. They may be classified as (a) core walls, (b) puddled core, and (c) water-tight face.

Core Wall.—A core wall consists of a concrete, masonry, timber, or metal wall or diaphram built within the dam usually near its center or toward the upper face and made as nearly impervious as possible. (See Plate XIV, Fig. A.) It is usually thin (Fig. 43) and is held in place by the adjacent mass of earth and rock. If built of concrete or masonry it is founded, if possible, upon solid

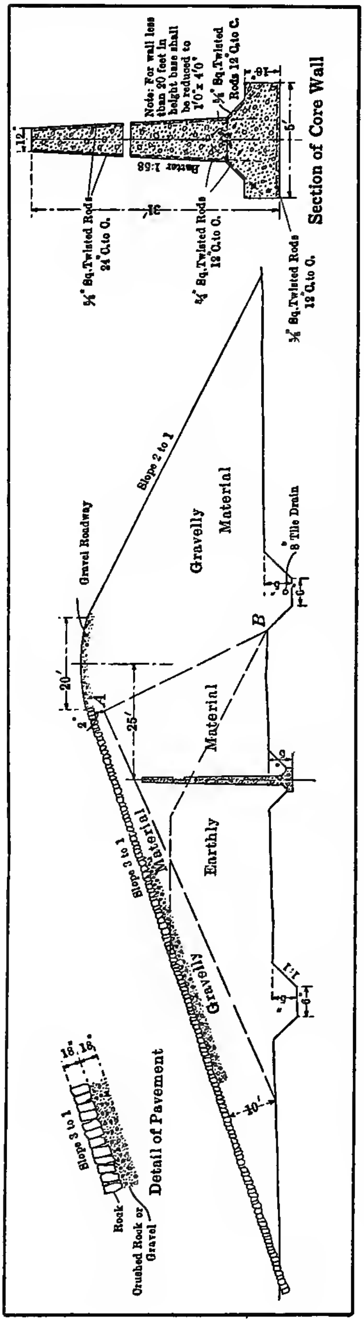
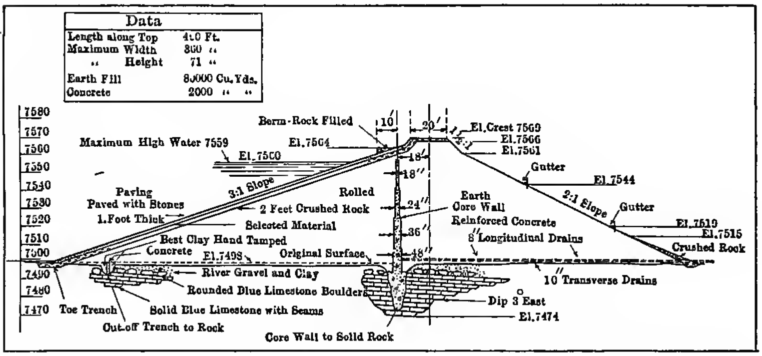


FIG. 43.—Section of earth dike with reinforced concrete core wall, Pathfinder dam, North Platte Project, Wyoming.

rock; where rock is some distance below the surface a narrow trench is excavated to it along the axis of the dam. This trench is then filled with the masonry or concrete. If it is impracticable to reach bedrock by digging the core wall may be founded upon steel or wooden sheet piling driven sufficiently deep to penetrate to an impervious stratum.

Instead of the concrete core wall, the sheet piling may be continued longitudinally up through the dam by a stout wooden or plank fence or bulkhead made water tight by sheathing or by plates of metal suitably joined or riveted together. These extend through the dam longitudinally from side to side of the valley. An objection to the use of a metal or wood cut-off wall or diaphragm in this connection is the liability to deterioration through the rotting or rusting of the material.

All core walls are subject to the further objection that the earth or main body of the dam in the course of settlement may shrink or pull away or that the wall may be ruptured by an equal settlement thus leaving plane of weakness or cracks through which water may percolate. It is very difficult, if not impossible, to make a good bond or tight joint between the core and the material composing the main body of the dam. It is held by some engineers that a thin core wall or diaphragm should not be relied upon to produce water-tightness in an earthen dam, but that it serves a useful purpose in preventing animals burrowing through the embankment. Nevertheless, it is believed there are some conditions where the building of a thin core wall, especially of concrete and the holding of this in place by earth and rock afford a satisfactory and economical method of construction. Such conditions have been met at the earth dam closing the outlet of Strawberry Valley in Utah, the section of the dam being given in Fig. 44.



Data	
Length along Top	410 Ft.
Maximum Width	800 "
" Height	71 "
Earth Fill	80000 Cu. Yds.
Concrete	2000 " "

FIG. 44.—Section of earth dam with concrete core wall and cut-off trenches, Strawberry River, Utah.

Puddle Core.—Instead of attempting to make a tight wall or diaphragm within the dam, it is practicable in most cases to secure as good, or better, results by careful selection of fine earth or clay, mixing this in proper amounts so as to secure a compact mud or puddle impervious to water. Skill and judgment must be employed in selecting, mixing, and placing the puddle, but if well done the resulting condition may be preferable to the building of a concrete or other core, because of the fact that the mass of the dam is more nearly homogenous and settlement occurs without disrupting or the opening of the joints or planes of seepage. An objection, however, to the puddle core is that it may be penetrated by burrowing animals, and if once punctured is eroded by the percolating waters.

Water-tight Face.—An impervious layer may under some conditions be placed on the upper or water face of the dam to advantage. This form of construction in many ways is more logical and conforms more to the theory of a dam, namely, of a water-tight wall or layer held in place by sufficient material to prevent its being broken or swept away. When this water-tight layer is put in the center as a core wall it cannot be inspected, but if placed on the upper surface it can be examined or repaired whenever water is drawn from the reservoir. A water-tight face is, however, difficult and expensive to construct and maintain.

To make this water-tight face, the simplest method employed in small dams is by the use of inclined wooden covering or sheathing. Planks are held in place by suitable means and the joints closed by battons or are caulked to form as nearly a water-tight surface as possible. In some instances sheets of iron or steel have been thus used, being provided with expansion joints and carefully protected from rusting by paint or various mixtures. Such metal covering is held in place by steel beams, or by a backing of concrete or similar material, and may be covered by a thin layer of concrete. The use of wood or steel may be considered as more or less of a temporary expedient, as the wood must be frequently renewed, owing to rapid decay due to the rise and fall of the water and alternate exposure to the waves and to the wind. The metal also corrodes, especially at the joints where it is not always easy to secure perfect covering.

Cement or asphalt or a combination of both are occasionally used for this water-tight layer, especially in small reservoirs for city supply. The expense is prohibitory for larger works needed for irrigation.

Care must be taken to provide adequate drainage for water which may percolate into the center of the dam through these wooden, metal or other coverings, and to see to it that the material composing the mass of the dam is sufficiently pervious to let this water escape without creating internal hydraulic pressure or uplift which will tend to reduce the weight of the dam and permit it to slide.

Cut-off Trenches.—The cut-off trenches are located in the upper portion and are made continuous with the core wall or less pervious materials of the dam. Usually one cut-off trench is considered sufficient, but conditions may arise where two or more may be desirable. The trenches are planned and excavated in accordance with evidence as to the character of the underlying material obtained by the test pits or drilled holes. They are usually as narrow as can be conveniently made and may be extended to an almost indefinite depth, if upon opening up the material is found to be notably pervious to water. In some cases, under earth dams, they have been carried down to a depth of nearly 100 ft. and then further extended, as before stated, by driving sheet piling at the bottom.

In refilling the cut-off trenches great care must be exercised in selecting the material and in packing it in place. Sufficient sand or gravel should be included with the fine clay or other available materials, to make a firm mixture, and one in which the voids will be filled as nearly as possible. The resulting mass should be moistened and tamped until thoroughly compacted.

In some cases, especially when the cut-off trench is carried to rock, it is desirable to build in it a thin wall of concrete. If the trench is very narrow and the walls of the excavation will stand sufficiently long, it can be filled with concrete and the trench thus used in place of wooden or other forms for holding the concrete in place during the time of setting.

Protection of Slopes.—The slopes of the dam must be protected from the erosive activities of the rain and wind. Any uncovered bank of earth is quickly carved and corrugated unless well protected. Such protection is afforded either by a pavement of stone or by a growth of grass or plants whose roots hold the earth in place.

On the water side the protection must be of the firmest possible nature, owing to the constant attack of the waves. As the water rises and falls in the reservoir and especially at points where exposed to the wind, the waves cut beaches or terraces and tend to leave the banks of the reservoir in a series of horizontal lines. On the outside or land side, the erosion due to the weather generally takes the form of nearly vertical lines and here the less expensive covering may be provided of turf or grass.

For the water slope, heavy stone or riprap is required. This should be so placed that the stones interlock, and that the sweep of the waves will not dislodge them. The foot of the slope must be carefully arranged to sustain the weight or resist any tendency to slide. The angle of the slope should be sufficiently flat so that the stone pavement will rest upon it. This angle is dependent upon the character of the underlying material. In the case of clay not well drained, the water penetrating beneath the pavement on even a relatively flat slope may cause the sloughing of the bank, carrying with it the stone pavement. (See Plate XIV, Figs. C and D.)

On the dry side also, the character of covering is dependent largely upon the material in the bank and plants and grasses selected must be with reference to the angle of slope and constituent material.

Drainage of Dam.—One of the elements of safety of an earthen structure is in preventing saturation especially on the lower or land side of the impervious layer or puddle core. It is assumed that the dam may be saturated to this diaphram or core and that a small amount of water will penetrate through it. This water and that which falls in rain upon the surface must be quickly conducted away so as to leave the lower side relatively dry and thus prevent the tendency to slipping or sliding resulting from the presence of wet or soggy material. In preparing foundations of the dam, drains must be arranged and tile of suitable size placed longitudinally to the dam in such a way as to catch and carry out to the lower toe any water which may be percolating through the puddle core. At different heights in the dam also other drains should in some cases be constructed for carrying the water out to the lower slope where it can be caught in suitable gutters.

Dikes.—The term dike is applied to low, long earth dams. usually built parallel to the general course of a river or along the shore of a body of water to prevent the land from being overflowed by floods in the river or by high tides or similar fluctuations in height of water.

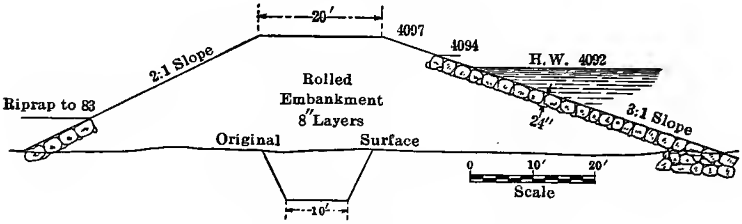


FIG. 45.—Cross-section of earth dike with pavement on water side.

The term dike is also applied to a long, relatively low extension of an earth dam where the topography of the country is such that the dam must be continued for some distance across low grounds. It frequently happens that in the prolongation of an earth dam the topography is such that rising ground cuts out the necessity of the dam or dike for a space of a few hundred or thousand feet and then a depression occurs which must be closed by a low structure which may be considered as a continuation of the main dam, in which case the term dike is often used for each of these smaller earth dams.

The principles of construction of dikes of this character is practically the same as those discussed for earth dams in general. One

FIG. A.—Concrete core wall in earth dam. Carlsbad Project, N. Mex.

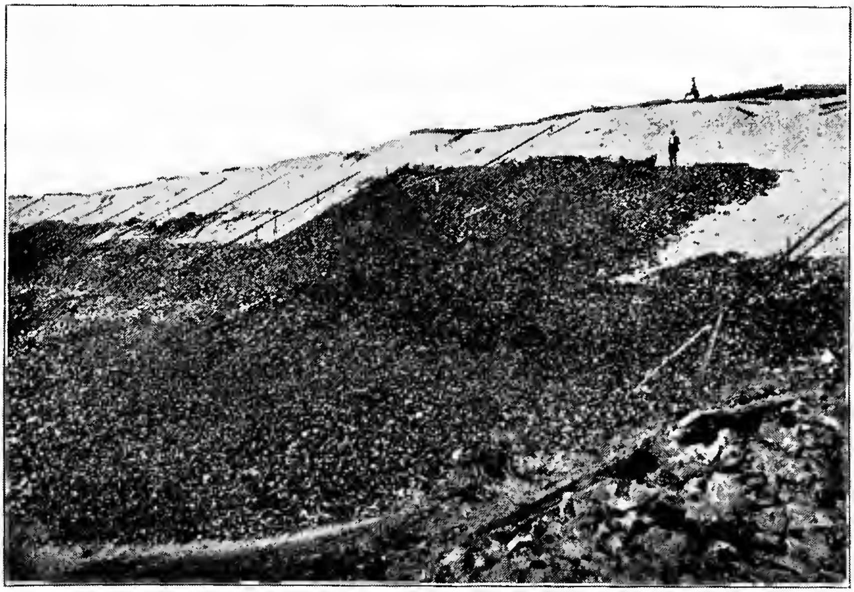


FIG. B.—Loose rock protection of earth dam on water side. Umatilla Project, Ore.

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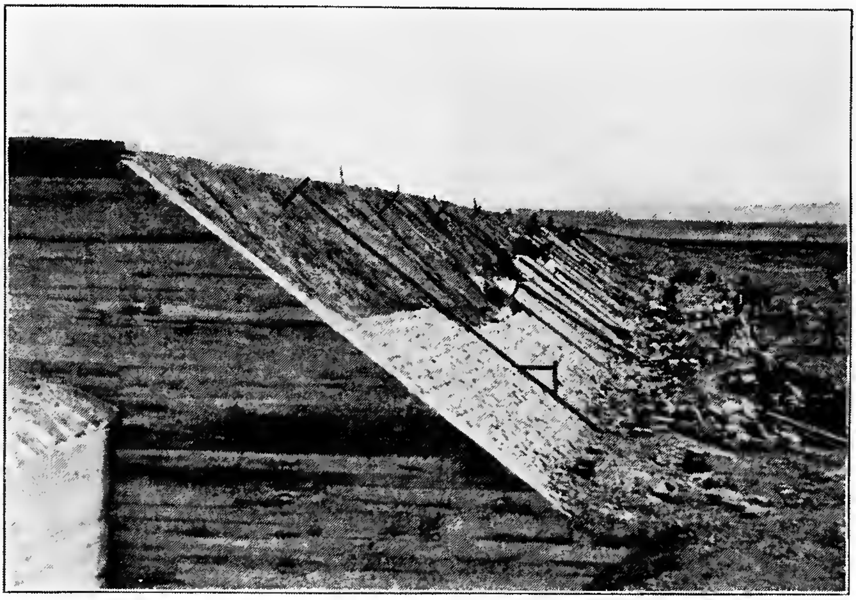

FIG. C.—Paving on water side of earth embankment. Belle Fourche River, So. Dak.

FIG. D.—Concrete block protection against wave action on earth dam. Belle Fourche Project, So. Dak.

or more cut-off trenches are provided and the water slopes paved, as indicated in Figs. 43 and 45 and on Plate XIV, Fig. B.

Limits of Height of Earth Dams.—A few earth dams have been built to a height of over 100 ft., but the majority of structures of unconsolidated materials do not exceed from 50 to 70 ft. in height. If carefully built, there is no reason for limiting the height, as it is conceivable that earth may be so selected, arranged, and piled up in such massive form as to form practically a range of hills or a barrier comparable to that built by nature. The mechanical or engineering difficulties are not great, but the limit to be placed is that of cost, since the width or base of any high structure, especially one of earth must be correspondingly great. The cost therefore increases rapidly with the height due to extra material which must be selected and handled and the greater care required to prevent defects in the work.

Examples of Earth Dams.—Of the higher earth dams some of the more noteworthy are those recently built by the Reclamation Service, the highest being that on the Belle Fourche project in South Dakota, across Owl Creek, 115 ft. in height, and 6,200 ft. long, containing 1,600,000 cu. yd. Also the dam on the Umatilla project in Oregon, known as the Cold Springs Dam, 98 ft high and 3,800 ft. long, containing 757,000 cu. yd. of earth and gravel and 32,500 cu. yd., of rock fill. For comparison with these may be cited the Tabeaud Dam in California, 123 ft. high, 635 ft. long and containing 370,350 cu. yd., also the San Leandro Dam in California, 125 ft. high, 500 ft. long, and containing 542,700 cu. yd.

CHAPTER XV

ROCK-FILL DAMS

Description.—A rock-fill dam consists essentially of a barrier or embankment of loose rock with its up-stream face covered with an impervious layer or blanket. It is the function of the rock portion of the structure to resist the pressure of the water and hold in position, against this pressure, the water-tight face, which in reality forms the dam.

The rock section of the dam may consist of large and small stones dropped or dumped into place with little or no attempt at systematic arrangement, each stone being allowed to take its own position. The width of base of the rock barrier is sufficient so that the weight of the stones and the friction between them prevents any tendency of the structure to overturn, or its parts to slide on each other. As compared to an earth dam, each component part or stone is relatively large and heavy. It is, therefore, held in place by its weight and also by the rough or angular projection of its neighbors.

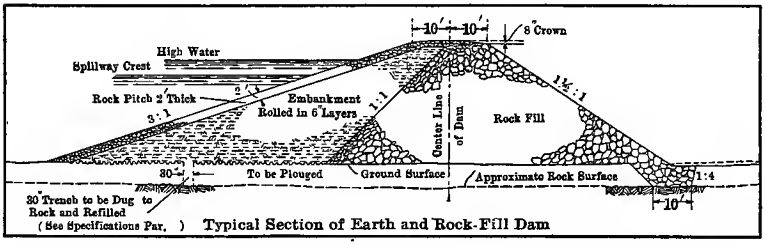

FIG. 46.—Typical section of earth and rock-fill dam, Clear Lake dam, Klamath Project, Oregon.

The water-tight portion or face of the dam may be of various materials, such for example, as wood, steel, concrete or earth. The more common of these, especially for dams constructed during the past few years, is earth. The thickness of this earth covering is made to vary slightly, due to the character of materials available and other local conditions. Its thickness also increases from the top to the base of the dam as shown in Fig. 46. For high dams the earth thus forms a considerable portion of the total materials required. Dams built in this manner, partly of rock and partly of earth are commonly designated as rock- and earth-fill dams.

Advantages over Earth Dams.—The principal advantage of rock-fill over earth dams is that the former is less likely to be injured or washed away by overtopping during extraordinary floods or unexpected occurrences. There is also some advantage in the methods of construction which may be employed, due to the fact that a limited quantity of water can be passed through the rock portion of the dam without serious injury.

If water rises in an ordinary earth dam, and finds a channel over or through it, the structure is doomed, as the component particles are too small to resist erosion. Such a failure may be rapid, due to the ease with which the earth is eroded and the flood thus let loose causes great damage. A rock-fill dam on the other hand may pass a considerable quantity of water over or through it without being washed away, or even seriously damaged. Even though the earth portion of the structure should be eroded and carried away through the loose rock, there is a probability of the latter holding and reducing in a great degree the magnitude of the flood.

In constructing a rock-fill dam, especially on a periodic stream, it is frequently an advantage to deposit the rock, or a portion of it, in running water, the earth or water-tight portion being built during the low water or dry stage of the stream. The rock in this case is dropped into the stream and partly washed into place, the slopes adjusting themselves while the water is flowing over or through the mass. This results in some waste of material, as there is a tendency for the rock to be washed down-stream below the assumed toe of the structure. Where plenty of material is at hand and cheaply moved, this may be no serious disadvantage. It is also possible to construct the water-tight portion of the dam in a stream of moderate size, by first covering the upper face of the loose rock with small stones which will be washed into the larger openings and then adding on top of this successive layers of gravel, sand and finally clay or other fine-grained material, thus forming an impervious blanket. This method of construction also results in loss of earth, as some of the fine grains are carried into or through the loose rock. Material, both earth and rock, if deposited in water are as a rule more firmly compacted and less liable to settlement than if built up dry.

Site to Which Adapted.—Almost any site suitable for an earth dam is equally well adapted to one of the rock-fill type, provided the necessary materials for its construction are at hand. The most favorable site is one with sufficient quantities of rock situated near it and at sufficient elevation so that it can be shot down and easily dumped into position. A soft bottom under the rock portion is not always an objection, especially if the rock is placed in running water. If the bed is soft, the larger rocks sink rapidly into it, the stream scours out the lighter material and the mass is worked by the water well into the foundation until securely held.

Foundation.—The remarks heretofore made relative to water-tightness of the foundation for an earth dam apply equally for a rock-fill one. The methods employed for preventing seepage under the dam apply also in one case as in the other. That is to say, a constituent part of the dam, such for example, as a curtain wall or a trench filled with water-tight material should be carried down to an impervious stratum such as rock or clay.

Wherever a rock-fill dam can be built in the dry, that is, where the foundation can be kept free from water during construction, the site to be occupied by the dam should be prepared by removing the lighter material. If a solid bottom can be reached, special attention should be given to the water or upper side of the dam. Here a cut-off trench should be put down or sheet piling driven if the underlying material is sufficiently permeable, the object being to provide a continuous diaphragm or sheet of impervious material extending from bedrock or from a heavy bed of clay upward into the impervious covering on the upper face of the dam. Behind or below this covering or blanket the stone should be arranged to form as compact a mass as possible, filling in the interstices between the larger blocks with spawls and small stone but leaving toward the lower side of the dam ample openings or drains for taking away any water which may penetrate to the center of the dam.

Materials.—One of the most important questions for consideration is that of obtaining economically a large amount of heavy stone for the body of the dam. This can be had usually from the cliffs or rock exposures which are to be found frequently on the sides of narrow mountain valleys or gorges, through which a river has cut its way. By undermining these in part or by placing explosives in advantageous manner, large quantities of rock may be loosened and thrown down in such position that they can be readily handled and placed in the dam. The small stones can usually be had as a result of the breaking up or moving of the larger pieces.

The size of rock used may be as large as can be handled by the facilities available. In order to give stability to the structure, the principal part of the rock-fill should be composed of stones weighing each a thousand pounds or more. The spaces between these large stones should be filled in with smaller ones. The upper face of the rock embankment should contain enough small stones and fine materials from the quarries to make it sufficiently tight to hold the earth-fill in place and prevent its being carried into the rock.

The gravel and earth covering, while it may be relatively small in cubical contents, frequently necessitates relatively large expenditures, as these must be carefully selected and placed. Where rock is abundant suitable gravel and earth may not be easily obtainable but must be brought from a distance. In selecting the materials for the earth-fill, the same, or greater precautions for water tightness should be taken as in selecting those for an earth dam. When a suitable mixture cannot be found in natural deposits, the materials should be analyzed and properly combined.

Section and Slopes.—The most advantageous section for a rock-fill dam, like an earth dam, cannot be determined by any known mathematical formulæ. It is known that dams of certain top width and slopes have stood successfully, but how much their dimensions might be reduced and still make a safe structure is a question which cannot be positively answered. The essential requirement is that the rock-fill shall be heavy enough to prevent sliding either upon the foundation or within the structure.

The slope of the down-stream face should be sufficiently flat to prevent any tendency of the rock sliding upon it or in other words it should be less than the angle of repose for the material used. The up-stream face of the rock-fill should be sufficiently inclined to cause the weight of the water-tight covering to be supported largely upon it. This will prevent the tendency for cracks being developed, due to unequal settlement. These conditions are fulfilled by a slope of about 1 1/2 to 1 for the down-stream and 1 or 1 1/4 to 1 for the up-stream face. Generally the up-stream slope of the earth covering should not be less than about 3 to 1.

The top width of the rock-fill may vary from 10 to 20 ft. and that of the earth-fill from 5 to 10 ft. depending upon the height of structure, and the distance below the top of the dam of maximum high water in the reservoir. For very low dams where flood conditions are not severe less top widths than these may be used with safety.

The up-stream slope, if of earth, should be protected from wave action and from sloughing by means of suitable paving or other covering. The down-stream slope generally needs no protection, being composed of heavy rock. The rock in this slope may be either hand placed or they may be dumped roughly to the neat lines. Hand placing, while adding somewhat to the general appearance, does not in any other way improve the work. In fact, it is doubtful if a slope of hand-placed rock can be made as durable as one of large stone dumped into position.

Water-tight Section.—There are various methods by means of which rock-fill dams are made water-tight. Each of these methods requires some form of water-tight face or section being placed on the upper side of the loose rock-fill.

In the earliest examples of rock-fill dams a wood facing was commonly used. It was generally made of two thicknesses of matched or tongue and grooved lumber held in place by being spiked to a timber framework which was securely anchored into the rock. This form of covering is not entirely satisfactory on account of the rapid decay of the timbers and also its tendency to leak after a few years service. Concrete facings have also been used to a limited extent. In these there is a tendency for the concrete to crack, due to unequal settlement in the dam. In this connection it may be well to state that no structure built of unconsolidated material, such as earth or loose rock is free from some slight settlement. This should be taken into account in planning the work.

In the more modern construction of rock-fill dams a covering of earth is commonly used on the up-stream side of the rock-fill. This earth section is some cases in rendered more impermeable by means of a puddle core of fine materials or by a core wall of concrete masonry as shown on Plate XV, Fig. A. In some instances walls made of metal plates have also been used in the body of the dams. Where metal is used it is coated with asphaltum or some similar rust-resisting substance and further protected from injury and corrosion by being backed with thin walls of concrete. One objection which has frequently been urged against the use of thin walls in a dam is that they cannot be reached for purposes of inspection and repairs.

It is the opinion of the writers where suitable puddle material is available that an earth section containing a carefully constructed puddle core is the most satisfactory means of securing water-tightness. Where a core wall is necessary on account of unsatisfactory materials for the earth section, one of concrete either plain or with enough reinforcement to prevent cracking is believed to be the most satisfactory type.

Seepage through a rock-fill dam, on account of its greater stability and more perfect drainage in the rock section, is not likely to prove as dangerous as in the ordinary earth dam. Despite this fact however, every reasonable precaution should be taken to reduce the seepage to a minimum.

CHAPTER XVI

MASONRY DAMS

Principles of Construction.—The masonry dam depends for its stability upon the weight of its component particles, and also upon the cohesive strength between these particles. It may be regarded as a monolith of series of monoliths, each of sufficient weight to prevent its overturning due to the pressure of the water and also having sufficient cohesive strength between the parts to prevent sliding and to a certain extent permit it to act as a beam or arch.

Comparing the masonry dam to earth- and rock-fill dams, these may be arranged in a series according to the relative size and cohesive force between the particles. At one extreme is the earth dam in which each grain of earth or sand, or pebble of gravel, is infinitely small compared to the total mass of the structure. These particles are loosely held together and if exposed may be blown away by the wind or washed away by rain or running water. The force of cohesion, if regarded at all, is insignificant.

Next in such a series is the rock-fill dam, in which the pieces of which it is composed as compared to those of the earth dam are relatively large, many of them being of sufficient size to be compared in a finite sense to the whole volume of the dam and so heavy that they cannot be blown by the winds or washed away by running water. With the masonry dam a further and last step in the series has been taken in that the component pieces are cemented together to form a single large mass, or at least to make a few blocks forming an appreciable portion of the whole and each as a unit capable of withstanding the force of the water against it.

In the masonry dam there is a factor of strength due to the condition that a section of the dam is not dependent wholly for its stability upon the weight of the component parts considered as loose particles. Any vertical section standing along will resist a force tending to slide it and also to a certain extent an overturning force by the cohesion of its parts the section being considered to act as a monolith having resistance to crushing and shear. Taking a horizontal section of the masonry dam its strength is increased by each portion acting upon those adjacent to it which causes it to behave as an arch, if the structure is curved, or to a certain extent as a beam or cantalever if the structure is straight.

In designing a masonry structure, consideration is given therefore not only to the weight of the material to be used, but to the form of its arrangement and especially to the binding together of the parts to resist the pressure brought against the whole mass and which tends to overturn or lift it.

Kinds of Masonry Dams.—Under this designation of masonry are included all structures which are built of large or small blocks or pieces, laid in some form of mortar or cement to cause the separate pieces to adhere. There are thus included not only the dams erected of carefully quarried and dressed stone with close-fitting joints but also those built of rough fragments not dressed to specified dimensions but which are carefully placed in mortar or cement in such way as to form tight joints, the irregular intervals between the large blocks being partly filled by smaller stones bedded in the mortar. The large blocks may weigh many tons or the material may have been crushed to small sizes, in which case, there results a dam composed of concrete. The essential factor is that the component masses, whether large or small, shall be carefully bedded and surrounded or incorporated in mortar or cement, so as to form a single mass.

An apparent exception may be noted where the masonry dam is built with expansion joints or planes of weakness dividing the structure into large sections, each of which is interlocked with its neighbor but is of such size or shape, as to be able to stand alone—acting as a separate pier or beam.

The typical masonry dam is one composed of carefully selected rock, quarry dressed, and with outer covering or skin on the upper and lower face, made of selected stones cut to dimensions such as to form ashlar masonry. These stones or especially those on the upper face resisting the water pressure are laid with extreme care, so that there will be as little leakage as possible between the joints. The interior of the section of the dam is usually composed of as large stones as can be handled, laid carefully to avoid horizontal joints, and having each stone well bedded against its neighbor, care being taken to keep the top or working surface as rough as possible in order that the tendency of slipping of parts of the structure along any plane may be avoided.

Rubble Concrete.—The masonry built of irregular masses of rock such as are obtained from the quarry, fitted into place without any considerable dressing excepting to remove loose fragments is included under the terms "rubble." For the construction of large dams rubble carefully laid in mortar is not only more economical but is preferable to the ordinary dressed stone, because of the fact that the joints between the rocks are irregular. If these joints are carefully filled with mortar or cement the resulting structure may be more nearly impervious to water. The dressing of the stones from the quarry and attempting to bring them to flat surfaces not only introduces large expense but unless the work is very carefully done, there is no resulting gain, so far as forming an impervious joint. The smooth surface introduces more or less of a plane of weakness as compared with the rough surface where one stone projects up into the space between others.

A typical rubble masonry dam is one in which the largest possible stone and rock are used, these being put in place by derrick or overhead cableways. The size of these may range from a ton up to 10 tons, or even 15 tons, dependent upon the strength of the machinery. Each large stone is carefully inspected to see that it is sound and that all of the loose fragments have been removed. It is then thoroughly washed, before being swung into place. A bed of soft mortar has previously been prepared and the large stone is placed carefully in it, being lifted, if necessary, once or twice to see that the stone bears firmly on all parts of the mortar bed. Spalls are then rammed in, around or partly under the rock, where possible and another bed is prepared alongside for a similar large rock, these not being allowed to touch, but a space of two inches or more is allowed between each projecting point. The result is what in nature would be called a coarse breccia, in which the individual fragments weigh tons, or what is sometimes called a "pudding stone" in which the "plums" are large irregular fragments. For the sake of appearances, such rubble structures are usually faced with selected rock, or the projecting inequalities broken off, to bring the structure within neat lines, but even without such finish the resulting work has a massive roughness consistent with its general character.

The proportion of large rock in Cyclopean rubble is determined largely by the question of expense. If the large pieces each several tons in weight exceed about 12 per cent. of the volume of the dam, the cost tends to increase, as it has been found that the time required to make the joints is excessive and the apparent

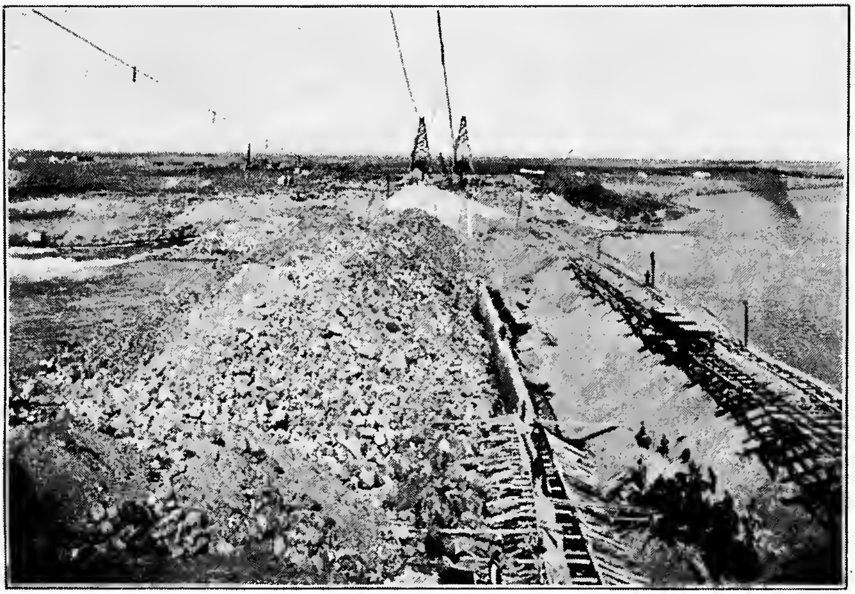

Fig. A.—Earth and rockfill dam under construction, with low concrete core wall, gravel and earth is being dumped on upper side with loose rock below, Minidoka, Idaho.

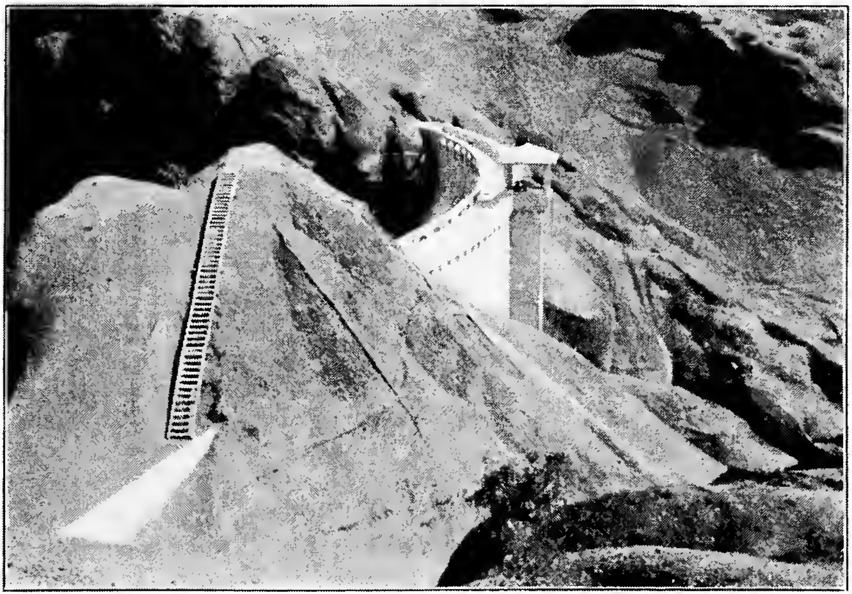

Fig. B.—Concrete structure for regulating floods. East Park dam, Orland Project, Cal.

FIG. C.—Rubble masonry dam; lower portion of Roosevelt Dam, Ariz. (See finished dam, Plate XI, Fig. D.)

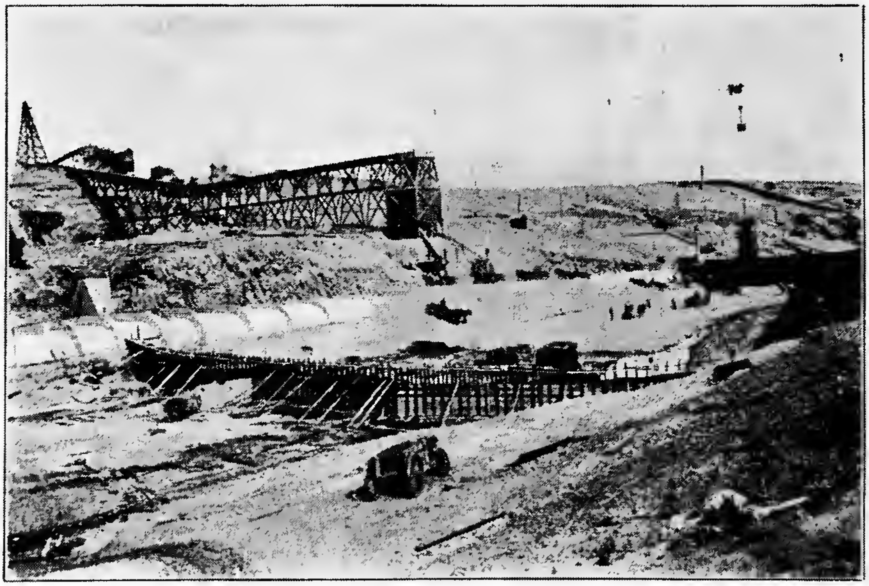

FIG. D.—Foundations for Lahontan Dam, Nev.; showing concrete conduit, conveying water through lower part of dam, with conveying plant in background.

gain in using the large rock is counterbalanced by the loss of time in bedding them.

If distinctly stratified rock is used in the dam, especially any pieces having a shaley structure, care should be taken not to bed these horizontally, but to place the rock in the dam in a vertical or inclined position so as to reduce the tendency to shear along the horizontal planes.

Foundations.—On account of the great weight of a masonry dam, the foundations must consist of solid rock. There may be exceptions where the masonry is of relatively small height and has great breadth of base or bearing surface, in which case it may be founded upon impervious clays or even on sand held in place by sheet piling or even by round wooden or masonry piles.

In preparing the foundation, they must necessarily be laid bare, the water being excluded by a cofferdam, or other means and all of the looser and weaker portions of the rock removed. In case there are open cracks or seams it may be necessary to excavate pockets or shafts to a depth or extent such as to clean out all of the poorer materials, filling in the cavities thus made with carefully placed concrete or masonry. The rock in place after being stripped in this way is left as rough as possible in order to make a good joint and is carefully washed to remove all of the smaller particles and enable the mortar to effect a complete bond.

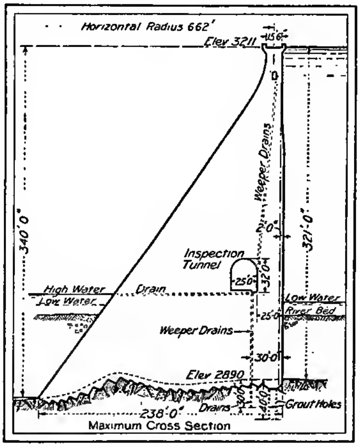

FIG. 47.—Typical section of masonry dam, Boise Project, Idaho.

Section.—The cross-section of a modern masonry dam has developed into a somewhat conventional form following certain general assumptions. On the upper or water side the dam is nearly vertical, having in some instances a light batter or forward projection of about 1 ft. horizontal to 20 vertical. On the down-stream side, the slope is about 1 ft. horizontal to from 1.5 to 2 ft. vertical. It is generally a straight line, or may be gently curved, the batter or slope being increased downward from about the middle height of the dam as shown in Fig. 47.

This form of section has been developed from theoretical considerations, verified by practical results. There are two principal forces to be considered: first, the downward pressure, or weight due to gravity of each portion of the dam acting upon the foundation or upon each horizontal layer or section of the dam; and second, the horizontal pressure or force of the water tending to push the dam down-stream or overturn it. There are other forces, such as "uplift" and ice thrust, of less immediate importance, but which are to be considered.

To compute the resultant of the two main forces, the dam is considered as consisting of an indefinite number of portions formed by taking successively lower and lower sections from the top down to the foundation. Beginning, for example, with the first 10 ft. of the top section, the center of gravity of the assumed section, in this case usually a rectangle, is taken and the downward force acting through this center of gravity is computed. The horizontal pressure of the water in the reservoir when full is also ascertained and shown as acting upon a point in the cross-section one-third of the height of the water above the assumed base. The lines of force cross at right angles. When graphically shown (Fig. 49) with length proportional to the relative amount of pressure in each case they enable the construction of a simple triangle of forces which gives the direction and amount of resultant pressure.

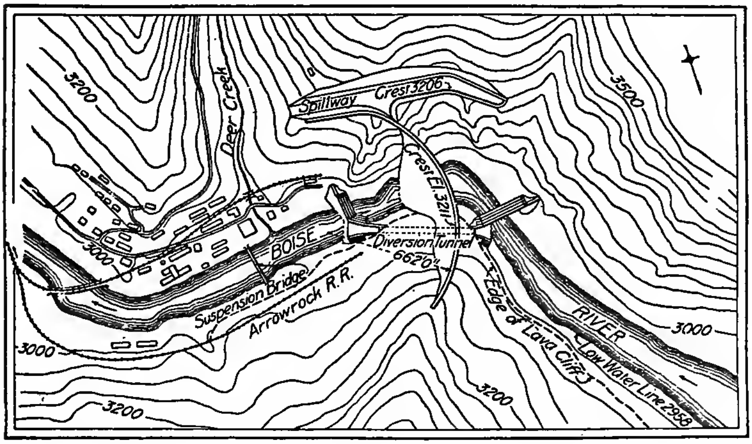

Fig. 48.—Location of dam and construction camp, Boise Project, Idaho.

This line of resultant force should evidently fall within the base of the portion of the dam under consideration, otherwise the structure might be overturned. In the earliest dams built the thickness was as a rule made excessive and the resultant line fell far within the section so that evidently there was a large waste of material. The question as to where the resultant line should fall has been under discussion among the engineers for many years, it being primarily a question of the factor of safety to be used. There has finally been adopted as more or less of a compromise a somewhat arbitrary rule to the effect that the resulting line of pressure with the reservoir full or empty should fall within the middle third of the base of each portion of the dam. The accompanying Fig. 49 gives graphically the analysis of pressures of the East Park Dam of the Orland project, California, in which it is assumed that the weight of concrete is 140 lb. per cubic foot, the weight of the water, 62.5 lb., the weight of the sand and gravel in river bed, 100 lb. per cubic foot. The only stresses computed were those due to the dam acting as a gravity section. The figures given at the bottom of each portion of this section are the minimum and maximum vertical unit stresses per square

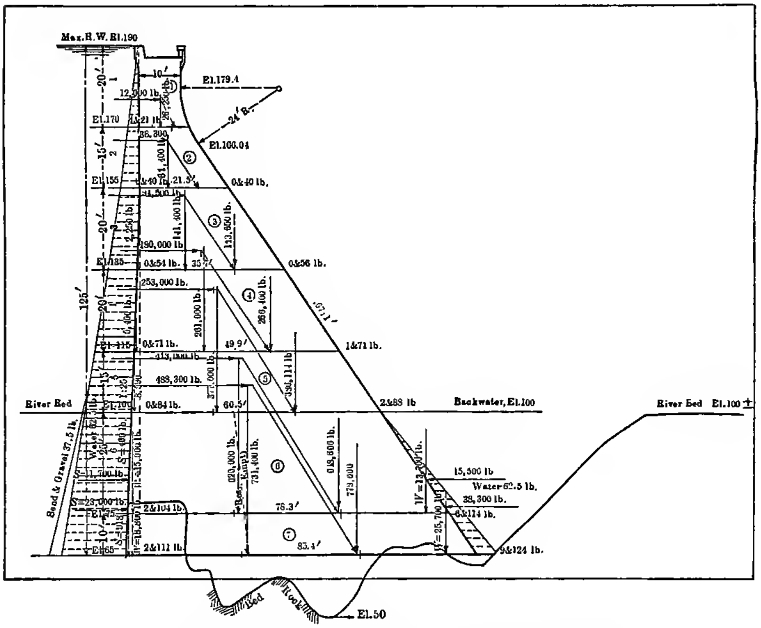

FIG. 49.—Graphic computation of stresses in masonry dam.

inch for the reservoir full and empty. The general location of this dam is given in Plate XV, Fig. B.

In addition to the ordinary static pressure of the water in the full reservoir there should also be considered in the case of dams in northern climates the probability of an increased pressure at the surface due to the formation of ice on the reservoir. What this pressure may be has not been determined. In many cases it is probable that it is so small as to be negligible. Observations on some of the large structures show that the ice against the dam is very thin, or in some cases there is open water throughout the winter. The surrounding land may be in such shape that the ice pressure if any is exerted along the shore line and not appreciably against the dam.

The maximum amount of ice pressure that has been assumed is upward of 44,000 lb. per linear foot. This adds notably to the required thickness of the dam, and it has been questioned as to whether it is necessary or wise to make provision for such large assumed forces.

Concrete.—The difference between rubble masonry and concrete is one of size of individual stones rather than of essential difference in kind. Instead of attempting to use the largest possible stones in the structure, the pieces are crushed to a small and nearly uniform size, and then mixed with the mortar or cement, so as to produce a mass which can be readily handled by shovels or small tools or which can be conveyed or allowed to flow into place through suitable conduits.

One of the great advantages of concrete construction is that of possible speed, the rate of depositing the concrete being dependent upon the size and economical arrangement of the crushing, conveying and mixing machinery which may be relatively compact; whereas, in the case of masonry, including cyclopean concrete, the speed of construction is often greatly reduced by congestion of the work and necessity of installing bulky machinery in a relatively small space, one operation interfering with or delaying another. With modern methods of mixing and delivering concrete into place through conduits, it is practicable to keep flowing to the dam a nearly continuous stream without one portion of the work interfering with another.

This speed of construction is an important consideration in the building of dams in localities where work must be expedited between flood seasons. By having made in advance suitable arrangements of the material and machinery, it is practicable to lay a large amount of concrete in a constricted space far more rapidly and economically than could be done in the case of large blocks of stone.

Another advantage possessed by concrete over ordinary masonry is that the mass can be made practically homogeneous and the stresses or strains in the finished structure may be more nearly anticipated and provided for by suitable expansion joints or other devices.

Upward Pressure.—No masonry or concrete structure is absolutely impervious and it is necessary to assume that water will find its way to a small extent under the foundations and into the interior of the dam. In many of the modern structures elaborate drains are provided to carry out to the lower side the water which may thus occur as minute springs or points of moisture. In addition to this certain allowances should be made in computing the strength of the structure to provide for the accumulated lifting or overturning forces of the water which may percolate under or through the mass and not freely escape at the lower side.

The amount of this upward pressure is dependent upon the height of water against the dam. It is assumed to be maximum at the water face and to decrease to nothing at the lower side. In computing the overturning forces acting upon the dam allowance should be made for the existence of this force and the thickness of the dam correspondingly increased unless perfect drainage is provided.

Curved Dams.—Each section of the masonry dam is usually computed as above noted on an assumption that it is to stand alone, without aid from adjacent vertical sections, but wherever the side walls or abutments are sufficiently firm and are not too far apart, it has been the custom to design the whole dam on a curved plan, so that it will act as a horizontal arch, transferring the horizontal pressure of the water in part from section to section and to the rock abutments.

The radius of curvature of this arch is generally from 400 to 600 ft. but may be more or less than this, in accordance with the length of the dam.

Multiple Arch Dams.—In the types of dams already described the force of the water is resisted by a solid mass of practically uniform section throughout the length of the dam. In this way a maximum of material is used and the question naturally arises as to whether certain portions of the section of the dam cannot be made thinner or, to consider it in another way, whether the retaining wall or curtain cannot be held in place by piers or buttresses, rather than by continuous mass of rock or earth.

This is particularly the case with concrete construction, where it is readily seen that the concrete dam being composed of more or less plastic material may be moulded into any form desired. The impervious blanket or curtain may be given a thickness only sufficient to prevent percolation and can be held in place by buttresses or struts designed of ample shape and form to hold this curtain against the pressure of the water. In other words, we may design a structure upon thoroughly scientific lines and without the unnecessary waste of material which is found in the usual solid dam.

These multiple arch or composite dams are especially suitable for conditions where economy of material is a prime requisite or where the foundations are of a somewhat doubtful character. The saving of the material is to a large extent offset by the difficulties of construction and in many cases it has been found more satisfactory to build the more simple, solid structure. There are, however, a number of types of composite dams which are coming into favor, in which the back or water-tight face of concrete, usually reinforced, is supported by suitable concrete arches or pillars upon a foundation or base adapted to the character of the underlying rock.

Internal Stresses.—In any structure where the masonry is laid under varying conditions of temperature and humidity, there must necessarily develop certain inequalities in loading. There is thus developed strains due to these inequalities, for example, the masonry laid during the extreme heat of summer when everything is expanded must necessarily shrink during the extreme cold of winter. For this reason, it is frequently specified that masonry structures in hot countries, especially those portions where the section is relatively thin, shall not be built during the time of greatest heat.

The largest stresses upon the masonry dam, especially on the thinner portion near the top, are those due to daily change of temperature. During the clear nights when the radian is greatest, the structure cools down and contracts. The morning sun may strike upon one side of the dam, heating it rapidly, while the other side is still cold, and by afternoon the conditions may be reversed, in that the opposite side is exposed to the hot sunlight. Thus there is a more or less continuous though minute movement of the structure and tendency to form temperature cracks, due to alternate lengthening and shortening of the structure. These intensify the action of the waters percolating through the mass from the upper side, and must be guarded against by increased thickness above what would theoretically be sufficient. The drying out of the mass of concrete is also a very important factor in developing shrinkage cracks.

Safe Limits for Foundations.—The amount of load which a foundation will sustain is dependent upon the texture and bedding of the rock. A fine-grained granite, for example, with few if any visible bedding planes and held in place by the weight of the adjacent strata is practically incompressible and will stand almost any weight which can be put upon it. On the other hand, porous volcanic rock or strata with open seams may be readily compressed under the weight of a mass of masonry.

It is customary to take samples of the material under consideration for foundation as well as those of the rock to be used for the structure and to apply crushing tests to determine the number of pounds or tons per square inch required to fracture the stone. This, of course, gives certain relative values for small samples of uniform size and texture but does not demonstrate how the rock will behave in large masses or when prevented from moving or expending laterally, as for example when in place and held by adjoining rock.

Based on the above assumptions the safe limits foı foundations and for material for masonry dam have been taken as from 25 to 30 tons per square foot or 400 lb. per square inch that is to say, in computing the weight upon the foundations and in designing the thickness of section of the dam, this has been increased until the pressure per square foot of the superimposed mass will not exceed the figures given. In this case, it is assumed that upon each square foot of bearing surface there will be imposed the weight of a shaft 1 ft. square and extending to a depth of the dam, plus the added pressure due to the component forces which may tend to overturn the dam and thus increase the pressure upon this point.

As a matter of fact, owing to the slight inequalities in bearing a somewhat greater pressure may be imposed upon one square foot or small area and correspondingly removed from another, so that compression or crushing to a small extent must take place before every square foot of the surface is brought into absolutely equal bearing.

The data upon the strength of various rocks have been obtained largely from tests made upon cubes of 1 in. or 2 in. on edge. These show that under compression these cubes will withstand a weight of from 20,000 to 40,000 lb. or even more per square inch, or from 10 to 20 tons. It is probable that in larger masses of indefinite extent the ability to resist crushing would be still greater. With limestone likewise, the crushing strength for small cubes has been ascertained to be from 14,000 to 20,000 lb. per square inch or from 7 to 10 tons.

Where the material underlying the foundation is relatively soft or porous, the foundations must be spread correspondingly to distribute the load, so that there can be no notable settlement after the structure is finished. Such settlements may result from either one of two principal causes; first, the actual compression vertically of the rock by which minute openings or joints are closed, or softer minerals decreased in bulk or, second, by the gradual flow of some of the lower layers. It is well known that even apparently solid rocks under great stress are slightly plastic and if around the sides of the foundations the rocks are not confined and held in place by adjacent rocks of equal hardness, there will be a tendency to flow. If properly held, however, even the softest rocks will sustain heavy weights as shown, for example, by the action of partly consolidated sandstone, or even of sand, which if held from lateral movement will sustain a large load.

Overflow Dams.—Where the masonry is designed to be overtopped by water, provision must be made not only for the increase in water pressure against the dam but also for the increased weight upon the structure due to carrying the water and also to the change of distribution of load. The most important consideration, however, is that of absorbing the energy of the falling water in such way that it will not injure the dam either by direct erosion or by undercutting of the toe or by impact or shock.

The conventional type of overflow dam is that with gently curving lower side on which the water overflowing the crest glides downward over the smooth surface and is gently deflected from a nearly vertical drop to a horizontal direction. The accompanying Fig. 50 gives the general outline of such a dam, together with the graphic analysis of the stresses. In estimating the forces acting upon the dam the assumption is made that the concrete weighs 147 lb. per cubic foot, that it contains 20 per cent. of rock and that the weight of the rock is 156 lb. per cubic foot, the average weight of the mixture in the dam being 149 lb. per cubic foot. The water is assumed to weigh 62.5 lb. per cubic foot and the flowing mud 57 1/2 lb. per cubic foot additional.

The figure under discussion is a section of the Granite Reef Dam on Salt River project, Arizona. It is provided with a tight concrete curtain wall 6 ft. wide under the upper face of the dam, and another curtain wall with wide holes to permit water to escape which may have penetrated beneath the dam. On the upper section the area is estimated at 184 sq. ft. and the weight of a section 1 ft. thick is given as 27,416 lb. On this the horizontal liquid pressure is estimated at 24,750 lb., and vertical liquid pressure at 5,040 lb.

The curved section is designed on the theory that the water should be forced to move in parallel lines down along the dam and

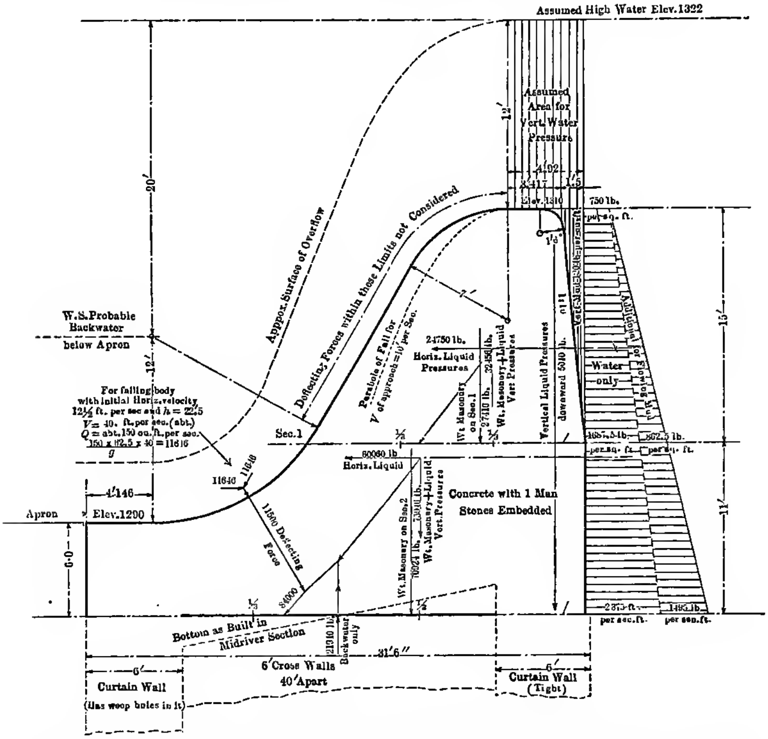

FIG. 50.—Cross-section of overflow dam with graphic analysis of stresses, Granite Reef Dam, Salt River Project, Arizona.

then be deflected to flow directly away from it. This theory is followed out very well so far as the behavior of the water on the face of the dam itself is concerned, but after the direction is changed to a point where it should leave the dam, there is usually a retardation resulting in a standing wave which offers a number of curious phenomena. The water, instead of continuing with gradually reduced velocity down-stream, gathers in a mass on the apron of the dam and sets up a churning or rotary motion which threatens to undercut the apron if near the lower edge.

Because of the difficulties involved by the standing wave or whirlpool at the lower toe of the overflow masonry dams, this type of dam has been made in many cases to depart from the conventional curve and to drop the water more nearly vertically rather than attempt to shoot it away from the dam in the horizontal lines. In this case, it is necessary to make the cross-section of the dam such that water flowing over the crest drops into a deep pool or water cushion. In descending vertically it strikes the return currents thus breaking up the force of water by work performed upon itself.

Protection of Lower Toe from Erosion.—The vulnerable point of most overflow dams is at the lower or down-stream toe. The character of the protection of this determines largely the profile of the lower side of the dam. If it is determined to deliver the water into the stream in a horizontal direction it is necessary to provide an apron extending down-stream for a considerable distance below the dam. The length of apron required is of course dependent upon the height of overflow and the volume of water passing over the dam. The lower end of this apron in turn is usually protected by heavy rock pavement, but even with the most elaborate device there is liable to occur erosion of the bottom and sides wherever there is a point of weakness. This is due to the whirling or gyratory movement of the water set up in changing its velocity and cross-section from that acquired by the fall over the dam to the relatively slower movement in the horizontal channel.

Various arbitrary rules have been given for the length of the apron, such, for example, that this should be five or ten times the height of the overfall, but in most cases the apron has been built of what is considered reasonably safe length, and then as experience is had, it has been lengthened by protecting the lower end.

In the case of structures which are designed on the opposite principle, namely, that of receiving into the stream channel the water falling directly over the dam, an entirely different arrangement is necessary. Instead of a smooth sloping apron a deep pool or water cushion is provided with walls of sufficient strength to resist the shock of the falling water. The theory of this form of construction is that the water should be forced to impinge upon itself and not upon any hard substance. The container therefore must be of sufficient size and strength so that the rotating or gyrating water in the pool will have sufficient volume to cushion the effect of the fall without expending energy immediately on the walls.

Safe Heights.—The heights of masonry dams have been steadily increased and larger structures each year are being designed on the basis of experience attained in building and operating the previously finished works. As in the case of ships or other structures each decade appears to see the limit of size, but this is quickly surpassed by the next design. Theoretically, there is no limit to size, as a masonry dam is an artificial reproduction of a hill or dike, such as those built by nature to heights of thousands of feet. It is merely a question of using enough material properly put together, the size being governed by the relation between the cost and the value of the result.

With increase of depth and consequent hydraulic pressure upon the natural cracks or pores in the foundations, and upon the joints in the masonry, it is necessary to observe greater precautions both in closing these cracks and in providing adequate weight and breadth of foundation to afford an ample factor of safety. In building a very high dam all of these matters are necessarily given greater study and consideration than in the case of the smaller works. The failures which have taken place have been of relatively low structures in which the problems seemed so simple that they have been neglected and the proper precautions have not been taken or the fundamentals carefully worked out on a theoretical and practical basis as on the higher structures.

Typical Masonry Dams.—The best-known masonry dams are those which have been built in connection with the water supply of large cities notably the dams on the Croton watershed for the city of New York, those of the Sudbury River for Boston, and those in the vicinity of San Francisco. More recently several notable structures have been designed and built by the Reclamation Service, particularly the Roosevelt Dam in Arizona and the Shoshone and Pathfinder in Wyoming.

The following list gives the location, name and type of the principal storage and diversion dams, whether of masonry or earth, constructed by the Reclamation Service, together with the maximum height, the length and the volume of the dam in cubic yards. The largest structure as far as cubical contents is the earth dam on the Belle Fourche project in South Dakota across Owl Creek, containing 1,600,000 cu. yd. of earth. Next in order to this are the lower and Upper Deerflat Reservoirs, Idaho, also earth banks, and then the

Cold Springs Dam, also of earth, on the Umatilla project in Oregon.

The largest of the masonry dams is that on the Salt River project in Arizona, the Roosevelt, containing 342,000 cu.yd. of masonry with a height of 280 ft. In comparison with this the Shoshone Dam in Wyoming, with a height of 328 ft., contains only 75,000 yd. of concrete, and the Pathfinder, 218 ft. high, on the North Platte River, in Wyoming, contains a little over 60,000 cu. yd.

PRINCIPAL STORAGE AND DIVERSION DAMS CONSTRUCTED BY THE U. S. RECLAMATION SERVICE

Project		Name	Type	Maximum height	Length, feet	Volume, cubic yards
Arizona	Salt River	Roosevelt	Rubble masonry arch gravel	280	1,170	342,000
Arizona	Salt River	Granite Reef	Rubble concrete weir	38	1,000	40,000[1]
Arizona and California	Yuma	Laguna	Indian weir (concrete and rock)	40	4,780	441,732[1]
California	Orland	East Park	Concrete gravity arch	139	250	12,200
Idaho	Boise	Boise	Rubble concrete weir	45	246	21,749[1]
Idaho	Boise	Upper Deer Flat	Earth	70	4,000	1,170,200
Idaho	Boise	Lower Deer Flat	Earth	40	7,200	1,180,800
Idaho	Minidoka	Minidoka	Rockfill-concrete regulating works	86	736	242,500
Idaho	Minidoka	Jackson Lake	Earth-concrete regulating works	40	3,256	66,649
Montana	Milk River	Dodson	Rockfill, timber crib	26	320	16,713[1]
Montana and North Dakota	Lower Yellowstone	Lower Yellowstone	Rockfill, timber weir	12	700	9,017[1]
Nebraska and Wyoming	North Platte	Pathfinder	Rubble masonry arch	218	432	60,210
Nebraska and Wyoming	North Platte	Whalen	Concrete weir and earthfill	29	2,500	80,740[1]
New Mexico	Carlsbad	Avalon	Earth and rockfill, concrete core	50	1,380	168,300
Oregon	Umatilla	Cold Springs	Earth	98	3,800	793,400
Oregon and California	Klamath	Clear Lake	Rockfill	33	790	56,600
South Dakota	Belle Fourche	Belle Fourche	Earth	115	6,200	1,600,000
South Dakota	Belle Fourche	Diversion	Concrete weir	23	400	12,150[1]
Washington	Okanogan	Conconully	Hydraulic earth	64	1,000	336,000
Washington	Yakima	Bumping L	Earth	45	3,500	233,800
Wyoming	Shoshone	Shoshone	Rubble concrete arch	328	200	75,000
Wyoming	Shoshone	Corbett	Reinforced concrete weir	18	400	4,951[1]

[1] NOTE.—Indicates diversion dams.

CHAPTER XVII

OUTLET WORKS

Capacity.—The capacity of the outlet of a reservoir or the means of drawing down the stored supply, must be ample to provide for the largest probable demand which will be made for water for irrigation and power purposes. In considering the size of outlet, account must be taken of the fact that it may be necessary to draw a full supply when the water in the reservoir is low and the head on the outlet comparatively small. For this reason computations for capacity of outlet should be based upon a minimum head in the reservoir. It is assumed that ample provision is made for a spillway capacity for floods but it may be desirable or even necessary to supplement this spillway by large capacity of outlets because of the fact that these draw water from the lower part of the reservoir if not too deep, and thus aid to a certain extent in keeping it clean by permitting the heavier muddy waters to escape. The spillways skim off the surface of the less muddy water; if the flood discharged is wholly over them, there is a tendency for the mud and silt carried down by the floods to be deposited in the deeper part of the reservoir near the dam. Where practicable as much of this deposit as possible should be drawn off through the lower outlets.

Location.—Experience has shown that outlet works for a deep reservoir should be located at various heights. Where, for example, the depth of water is considerably over 100 ft. dependence should not be placed wholly upon the sluices or gates placed near the bottom of the reservoirs, as these are apt to be partly buried in mud or silt. The erosive effects of the muddy waters under this head is also so great that few materials can withstand it. In planning the outlet works, therefore, arrangements should be made to draw water under heads of not to greatly exceed 60 to 70 ft. and to use the lower sluices only when the reservoir has been drawn down to a considerable degree, or when it may be necessary to flush the lower portion of the reservoir immediately adjacent to the dam.

The location of the outlet works must be governed largely by consideration of the safety of the structure. Wherever practicable, they should be built in tunnel in the natural rock of the side walls.

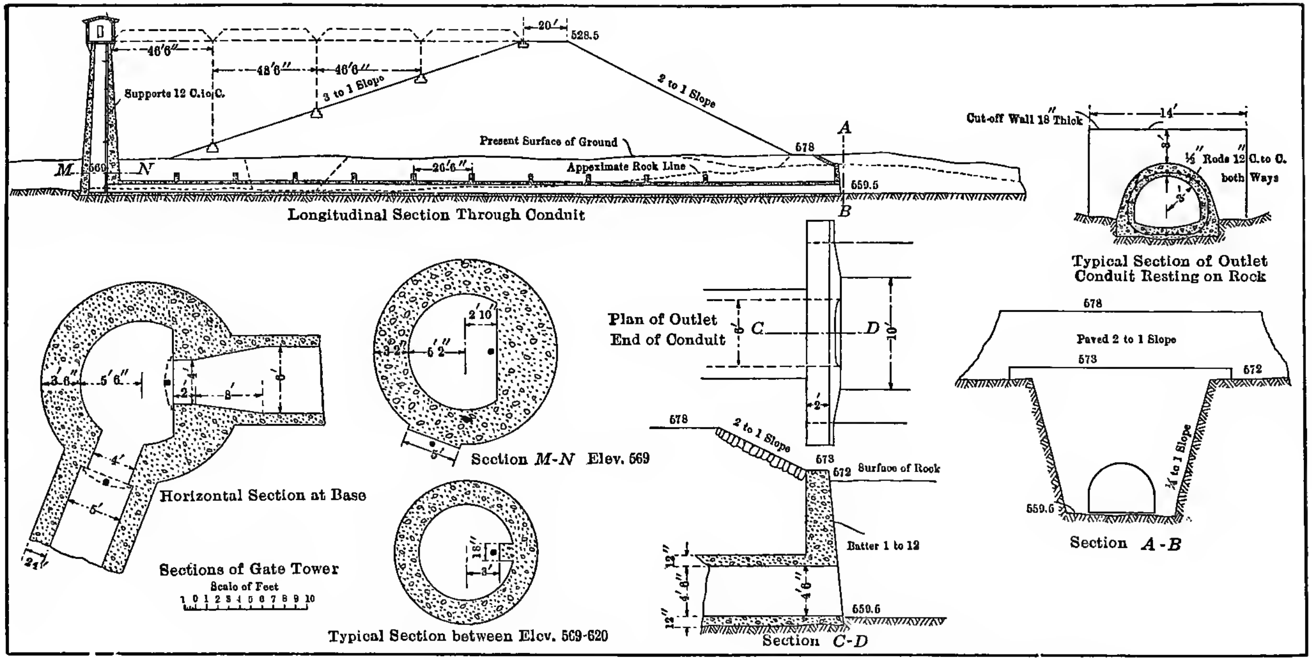

FIG. 51.—Section showing details of outlet works through Cold Spring Dam, Umatilla Project, Oregon.

Occasionally conditions are such that it is necessary to put the outlet through the dam or on the foundations. In such cases extraordinary precautions must be taken to prevent water following along the outlet conduits or pipes, and to guard against any unequal settling of the dam, due to this point of weakness.

Location of Gates.—The gates which control the outlet of a reservoir should be so located that when closed they exclude water from entering the conduit or channel through which water is to be discharged. This is usually accomplished by locating the gates at the upper end as shown in Fig. 51. If the gates are placed far back in the body of the dam, the water standing against them when closed exerts the full pressure of the reservoir head on the walls of the conduit and may find entrance into the dam itself by percolation through these walls. For dams with flat up-stream slopes the placing of the gates at the upper end of the outlet conduit renders them more or less difficult of access.

The two conditions of accessibility and safety are combined with difficulty and it is sometimes necessary to have more or less of a compromise. As a rule, the gates are protected by being installed within a solid masonry chamber as near as possible to the upper face of the dam, the chamber walls being projected upward into a tower within which the necessary mechanism is located. The usual practice is to provide the upper end of each outlet with valves or gates in duplicate, so that if one set fails the other can be operated. There is, however, opposition to this course, as it has been urged that these gates may be multiplied indefinitely without eliminating all risk of failure. In the recently designed Arrowrock Dam on the Boise River, Idaho, an exceedingly strong gate protected by a grillage is to be placed near the up-stream face to be used as a bottom sluice and not to be opened under a head of over 60 ft. There are also to be built in the lower portion of the dam several gates at various elevations, each being supplied with an independent conduit. Each of these openings can be closed by means of stop planks at low stages of the reservoir and repairs made to the gates. By this means they are rendered more accessible than would be the case if placed in a tunnel.

Gate Towers.—Access to the gates controlling the outlets to reservoirs is usually provided by means of vertical towers or shafts supported on top of the gate chambers and carried up above the high-water level. Where the upper face of the dam is vertical, or nearly so, as in the case of a masonry dam, the gate tower is usually built

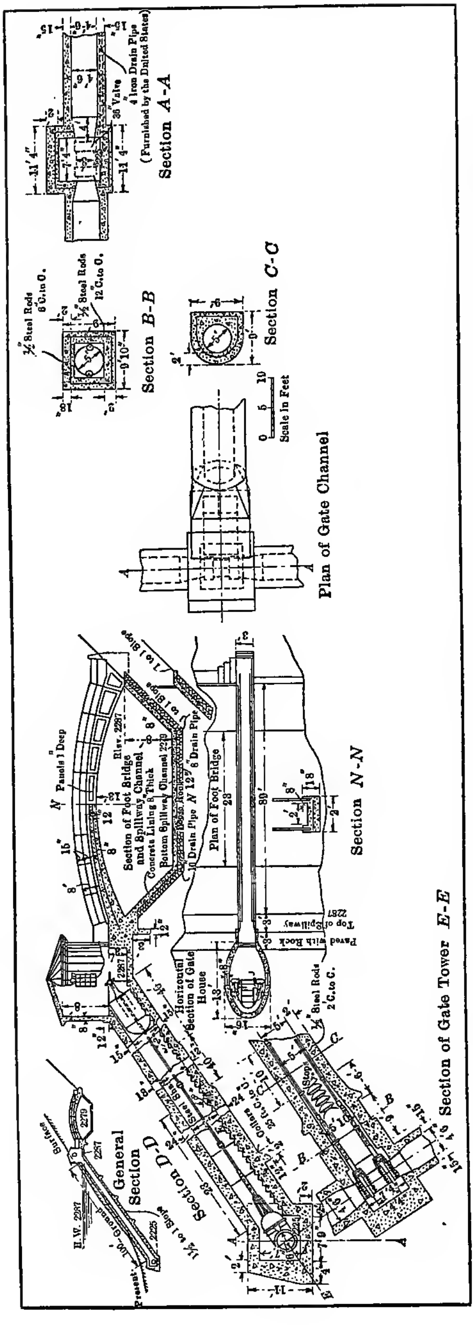

FIG. 52.—Inclined gate tower and section of spillway, Conconully Dam, Okanogan Project, Washington.

against it. In some instances access to the gates is provided by means of a shaft built in the body of the dam. This, however, may introduce complications both of reaching and operating the gate and possible unequal settlement of the structure.

For earth or rock-fill dams with flat upper slopes, the gate tower is generally carried up as an independent structure, access to it being provided by means of a bridge either from the shore or top of the dam. In some cases inclined valves have been tried, such that the operating mechanism lies along the sloping upper face of the dam as shown in Fig. 52. A disadvantage of these is the difficulty of operating and inspecting in this inclined position. In cold climates some difficulty has been experienced, due to the pressure of ice against gate towers constructed independent of the dam. The strength which a tower must have to resist the pressure of ice under varying conditions is difficult to determine with certainty.

Openings to gate towers are usually provided so that water may be drawn from various elevations in the reservoir. Occasionally the tower is divided into compartments so that water can be shut off from one or other of the gates and drawn out, permitting inspection and repairs.

Operation of Gates.—The gates or valves of low dams are operated usually by a screw lifting device, the stem of the screw being continued upward through the masonry or within the tower to a point above high-water level where suitable capstan or other mechanism for raising and lowering the gates is installed.

Where the depth of the reservoir is very considerable, or over say 60 ft., vertical hydraulic devices have been successfully tried for operating the gate, these being driven by small pump or motor. The piston in this case is located as nearly as possible above the gates to be raised and the piston rod operates through a stuffing box leading from the top of the gate into a water-tight chamber immediately over the top of the gates.

Erosion due to High Velocities.—Large gates or valves under high pressure offer a number of problems and require special design. The two chief points of difficulty encountered are, first, the erosion due to water issuing through the gates under high velocity, especially when carrying mud or sand, and second, the vibration or chattering of the gates due to the current of the water passing over the sharp edges, or around angular material.

There are some curious phenomena in connection with erosion. On the one hand the hardest of materials may be rapidly cut by the

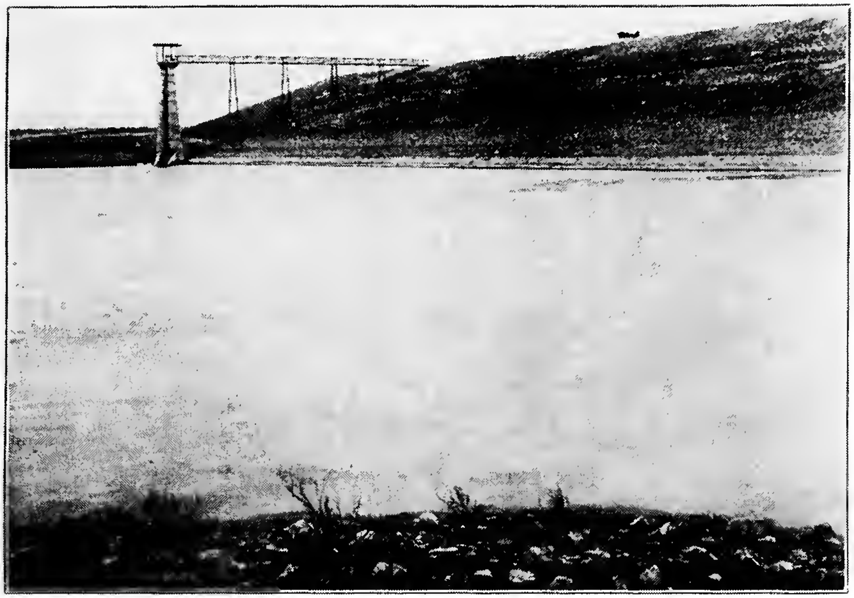

FIG. A.—Gate tower and bridge from earth dam, forming Cold Springs Reservoir. Umatilla Project, Ore.

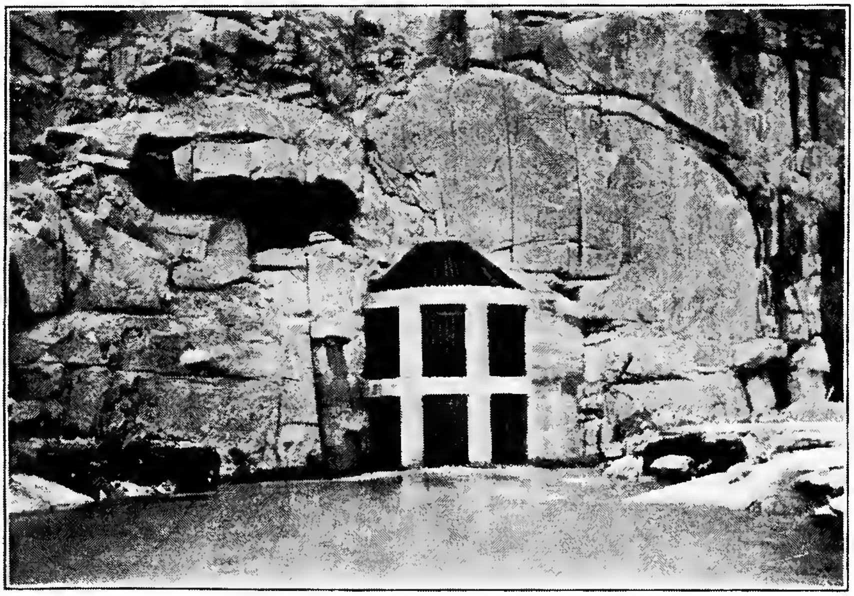

FIG. B.—Grillage protecting entrance to gates. Pathfinder Reservoir. North Platte Project, Wyo.

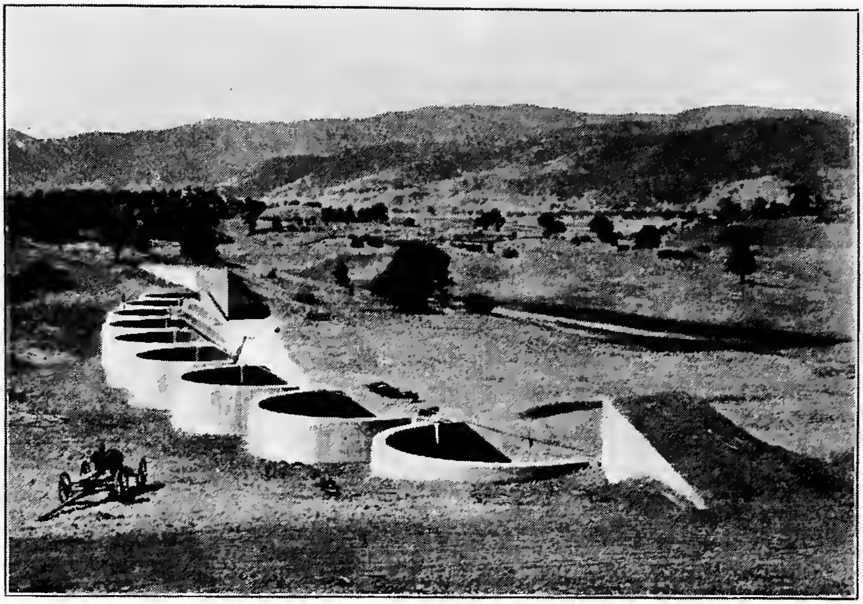

FIG. C.—Spillway with effective lengths increased by curved outlines. Orland Project, Colo.

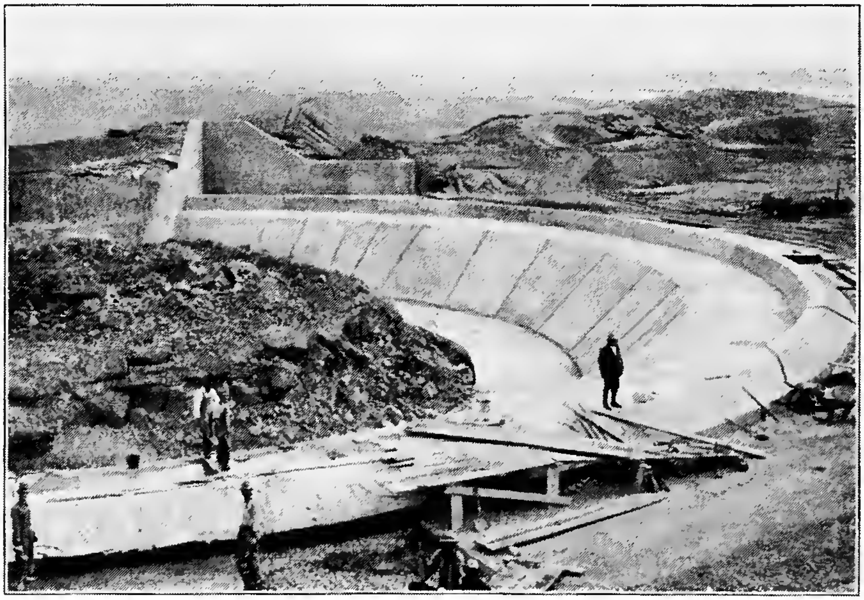

FIG. D.—Spillway for earth dam. Belle Fourche Project, So. Dak.

sand blasts and the best concrete carved into fantastic forms; on the other hand moss may be found growing on the edge of channels where such velocities are obtained. The problem is largely that of the character of the internal motions caused by the form of the orifice. This is illustrated in the case of a jet or nozzle where it has been shown that, for example, with a needle nozzle and with a certain shape of bucket of water wheel, the water will issue in straight lines and be deflected with the minimum erosion; whereas, with a slightly differing form of outlet internal currents are set up, causing a large amount of wear.

Experience has shown that the conduit leading away from any large gate or valve operating under high pressure should have as direct and straight an opening to the outer air as possible and with a slight constriction beyond the gates so that the maximum pressure will be borne by the outlet conduit and not by the gate itself when wide open.

Vibration of Gates.—All forms of valves in which a portion is under tension are subject to serious vibration. For this reason the balanced or needle valves with all the material in compression are preferable wherever they can be used. The tendency to vibrate is reduced and the wave movement is rendered practically negligible in well-designed valves of this character. The cause of vibrations may be attributed to three different classes of forces which when acting alone may be negligible but when acting in unison produce serious results. Each of these tends to cause a certain amount of motion, which may be neutralized in part by the other but when by chance the time interval happens to coincide the motion is amplified.

The forces causing vibration may be divided into three classes:

(1) Wave action.
(2) Pendulum action.
(3) Reed action.

(1) The wave action or rather the interval of action is that due to the length of wave in the water. It is assumed that the velocity of wave motion in the open air is 1,090 ft. per second. In the more dense medium of fresh water, the velocity of the pressure wave is generally taken at about 4,500 ft. per second in an open body of water such as a lake, while a safe average in concrete-lined conduits may be taken as 3,300 ft. per second. This pressure wave is set up on the occurrence of a slight disturbance or motion of the gate and continues indefinitely.

(2) Any sliding gate hung vertically becomes in effect a pendulum having a very slight range of swing. If this pendulum length happens to coincide in some simple arithmetical relation with the length of the pressure wave and thus the two happen to act in unison, the intensity of the motion is increased.

(3) The lower edge of the partly opened gate being supported at each side acts as a beam and the edge partakes of the nature of a reed such as that of an organ but having an extremely low tone or rate of vibration. This vibration following the laws of harmonics may be synchronous at intervals with the pressure wave and pendulum motion so that it may be conceivable that these three, namely, the pressure wave, the pendulum wave and the reed wave may at some interval occur on the same beat and their amplitude or destructive action be thus greatly increased.

Observation has shown that on structures even of great solidity the opening of the gates to a certain point causes vibrations to be set up and transmitted to a distance such as to be terrifying to the observer, destructive to lighter machinery, and possible to the structure itself. When, however, the gates are raised or lowered out of this particular position, the vibrations are reduced and continue with more or less magnitude, according to the dimensions and shape of the outlet.

This vibration or chattering of large gates under high head is comparable in part to the action of the steam whistle, in which a current of air or steam striking a thin plate or reed causes it to spring forward, then it reacts backward through a minute space, these alterations following with such great speed as to set up waves producing sound. In the case of the gate, instead of the vibrating reed we have a very large structure set in relatively slow vibration so that each individual impact is noticeable.

The vibrations are dependent upon the degree to which the gates are opened. As the gate is raised from its seat the motion begins slightly and usually reaches its maximum with a half-opened or three-quarter aperture, ceasing as the gate is pulled back into its recess, unless the lower edge is fully exposed to the current of water.

The continuous vibration tends to loosen every joint and bolt, finding every point of weakness so that in some cases it is necessary to open the gate completely or open and close it at short intervals, in order to save the structure. The vibration when the gate is fully open can be guarded against as before stated by having a constriction in the solid conduit beyond the gate.

Character of Gates.—The lowest outlets for deep reservoir, especially where liable to be buried in sediment, should have rectangular slide gates without roller or other complicated form of bearing. It has been found advisable to use relatively broad, firm bearing strips of composition metal somewhat of the character of bronze, the two surfaces being made of slightly different composition for the reason that if both bearing faces, namely that on the frame and that on the valve, are identical in composition there is a tendency to "freeze" in that the two metal surfaces of identical character under this high head cohere probably through molecular action. If, however, there is a slight difference in composition the molecular structure appears to have sufficient difference to prevent this so-called freezing.

These gates may be raised vertically by stems operated by oil-pressure cylinders protected in such way as to prevent the entrance of grit. The square form of gate has been found most desirable as against the round seat, as this affords a more perfect sliding surface and has less tendency to displacement when the gate is partly open. For higher valves not buried in sediment various forms of needle valves are preferable. All regulation of the full reservoir should be done with valves of this character.

The lower slide valves or gates of the reservoir should never be used for regulation but if necessary to open them they should be drawn completely back into their sockets and not allowed to remain in a partly open position on account of the excessive erosion and vibration which is set up. The opening as before stated should be into as nearly a straight smooth conduit as possible, gradually changing from rectangular form at the gate to circular form and lined both above and below the valve with cast-iron pipe and continued by concrete slightly diminishing in sectional area until the conduit is at least 25 per cent. smaller than the opening of the gate.

Where there are several gates each should open into a separate conduit and these conduits should not unite but continue, each independently to the outer air.

One of the important details of closure of flat-slide valves or gates of this kind is in the character of the contact of the lower edge. As this approaches the seat or bottom the scouring effect under the gate is greatly increased and ordinary metal is quickly cut out or destroyed. It has been found by experience that a relatively soft seat composed of a bar of lead or even of timber if depressed slightly below the floor will not be notably eroded and permits the seating of the gate and complete closure even under high heads or unfavorable surroundings. The type of gate seat thus found most advantageous is one where a groove is filled with a lead base, the top of which is depressed slightly below the floor line.

In order to overcome the difficulties due to high heads a type of balanced valve has been successfully used on several of the reservoirs built by the Reclamation Service the general outlines of which are shown in Fig. 53. The valve is easily operated by slight adjustment of the pressure in the cylinder which carries the conical plug or needle point, the destructive effect of the escaping water being largely neutrilized by this form of orifice.

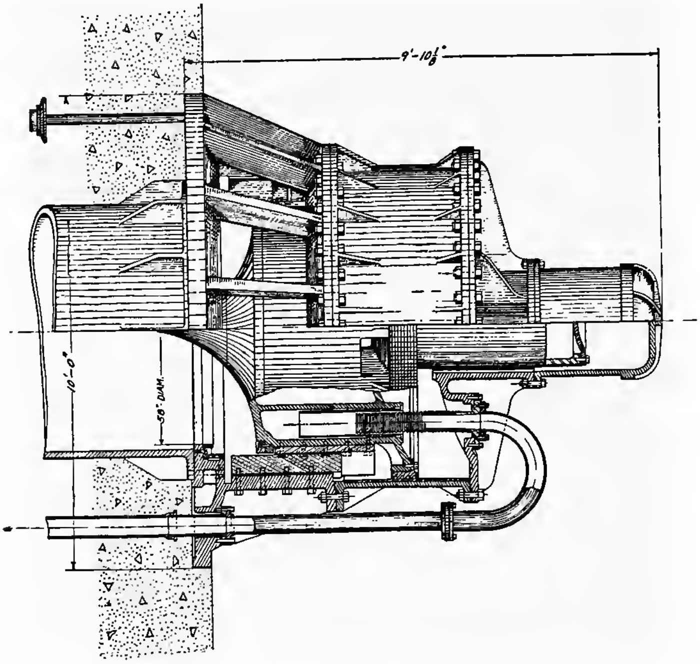

FIG. 53.—Balanced valve for regulating reservoir discharge under high heads. Pathfinder dam, Wyoming.

Fishways.—Where diversion dams are placed in perennial streams, it is usually required by state law that some form of fishway or ladder be built so as to permit the fish to pass the obstruction. The essential features are an inclined way on the slope of about one in four, provided with compartments making a series of boxes

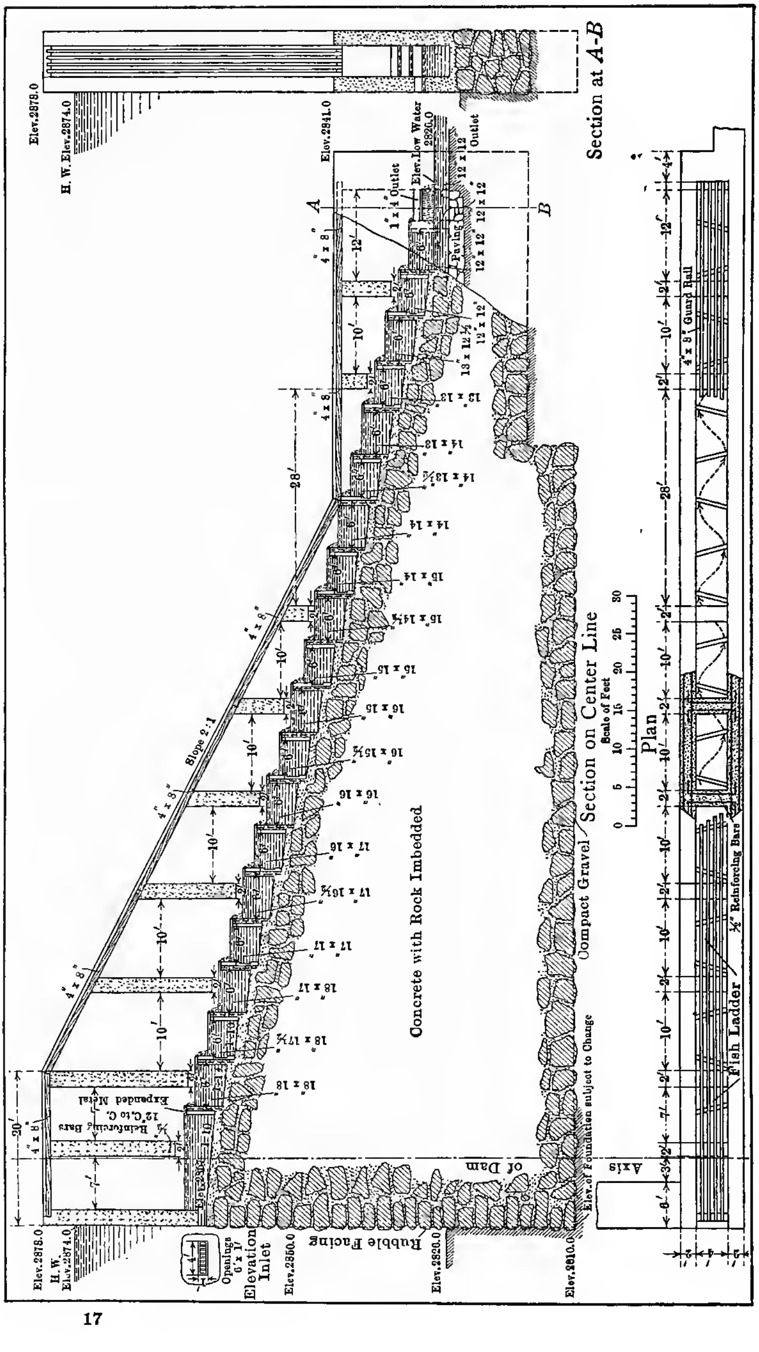

FIG. 54,—Fish ladder, Boise River dam, Idaho.

open at the top. From the top down each is successively lower, the water flowing from the higher into the lower down this slope.

A supply of water of at least 5 cu. ft. per second is usually necessary to operate a fish ladder of this character. The water may be allowed to spill over the edges from one box or compartment to the next and also a portion may flow through a small rectangular opening in the lower corner of each compartment. These openings are not placed in line with each other, but occupy successive alternate lower corners of the partitions, so that the water entering one compartment seeks the lower corner where it escapes through the opening usually 8 in. high by 12 in. wide. It then flows diagonally across the next compartment to the lower corner and so on, there being formed a succession of pools in which the fish can rest, and then dart through the submerged opening or they may leap over the crest into the next pool as shown in Fig. 54.

The partitions are not arranged at right angles to the slope but are inclined so that the water flowing through them will wash the sediment into the lower corner and out into the next compartment.

For a dam 20 ft. high, the runway would extend 80 ft., and so on. Care must be taken to have the lower end of the fishway brought into the pool below the dam and into water where the fish will readily find entrance.

Spillway Requirements.—A spillway consists of an opening or space provided in or at the side of a hydraulic structure, such as a dam or canal, and in such position that when the water rises above a certain elevation, it will escape through this opening into a channel from which it can be delivered usually to natural drainage line and with the least injury or inconvenience. As a rule some form of structure must be provided for a spillway, although in rare cases, conditions may be utilized in such way as to permit water to escape over the natural rock surface. Even in this case, however, it is usually necessary to trim the rock and provide an artificially leveled lip or sill over which the water may flow.

The first requirement is that the spillway shall have ample length and capacity, so that before the water rises above the designated safe level, it will begin to escape in a broad thin sheet, and not continue to rise rapidly to a height which will endanger the works. Next to the width are the considerations of permanency and strength, as a spillway may be called upon to handle large volumes of water coming quickly during the time of extraordinary rains, causing floods.

Spillway Design.—The design of any form of spillway is largely controlled by the surrounding conditions, more perhaps than in many other structures in the irrigation system. In the case of the storage dam the spillway location must be governed by the topography and the design affected by the natural slopes which lead away from the point of overflow. Sometimes it is almost impossible to find a suitable point, and it becomes necessary to modify the shape of the dam, lowering a part of the crest so as to provide a spillway over one end, as for example, on the new Croton Dam for the City of New York, where the right-hand end of the dam is curved upstream practically parallel with the side walls and prolonged in a low lip over which the water pours into a broad flume cut in the rocky side. A similar principle is used where a canal leading from the reservoir is enlarged at its upper end, as in the case of the Avalon Dam on the Carlsbad project, New Mexico. This permits taking care of a part of the flood water by discharging it from behind the dam into the head of the enlarged canal. It is there allowed to escape by overflowing the masonry edge of the canal or let out through large valves located in the bottom of a canal.

It is also desirable in some instances to design the spillway so that it can be provided with automatic gates or flash boards arranged that water can be held up on the spillway to the limit of safety. When it rises rbove a certain point, the gates are opened automatically or by hand. The simplest device of this kind is to build a small broad bank or ridge of earth on top of the concrete or masonry spillway. This for a time will hold back the water to a depth of say 2 or 3 ft., but when it is overtopped the earth is quickly swept away, thus releasing the excess water.

Determination of Capacity.—The tendency in designing spillways is to make them too small and in estimating the capacity required to base the figures upon assumptions as to the usual flood conditions. It should be remembered, however, that during the life of the structure or during the coming century, there will occur some one or more extraordinary combinations of rainfall or melting of snow, which will produce floods, exceeding the previously known maximum. It is to provide for these extraordinary conditions that the spillway must be designed. For example, on Cache Creek, a tributary of Sacramento River in California, the observations indicated a maximum flood of about 20,000 second-feet, but from various indications one of the engineers figured out a possible, although improbable flood during earlier years reaching 60,000 second-feet. This figure was generally regarded as almost absurd, but upon the basis of these extreme assumptions, a spillway capacity of 60,000 second-feet was provided. It was hardly finished before a flood occurred, such as had never before been known, with a probable maximum of 65,000 second-feet. Had not the spillway been built of a size which was laughed at, the structure would probably have been swept away. The lesson to be enforced is that the engineer in such cases must be prepared for criticism and ridicule by less well-informed people for building very large and somewhat expensive spillway openings for structures, especially storage dams where there is a large catchment area upon which storms may occur.

The determination of the size of the spillway must be based upon a knowledge of the area which is drained and upon measurements or estimates of floods which have previously occurred. It is essential to study the rainfall records and the combinations of flood which may arise from unusual storms occurring over one or another part or the whole of the catchment area.

If, for example, the annual rainfall is 15 in. and the catchment area consists of undulating plains and foothills, the ordinary discharge following a well-distributed rain may be practically nothing at the point of storage. Experience has shown, however, that the greater part of the annual rainfall may occur in a few days and 6 or 7 in. of rain may fall during one of these so-called cloud bursts. Where, under ordinary circumstances, this rain would be distributed through several weeks or months and would be lost daily by evaporation and seepage, it now is brought together in the usually dry channels and comes rushing down to the point of storage, creating a flood which moves large boulders and overtops works which have stood perhaps for several decades.

It is necessary, therefore, to assume these extreme conditions and provide for a possible runoff of say 50 per cent. of the storm or for at least 2 or 3 in. of rainfall over the area, even though this may not occur more than once in a lifetime.

Location and Type.—Wherever practicable, the spillway should be located away from the dam or principal structure which it is designed to protect, in order to guard against any backcutting or other destructive action due to the passage of a great volume of water during a short period. It is frequently necessary, however, on account of the topography of the country to construct the spillways as part of the masonry dam, and to permit the waste water to flow into the stream channel immediately below the dam. In such case provision must be made against the water backing up against lower toe of the dam and by the gyratory motion of the water undercutting or weakening the foundations. In the case of earth dams, it is particularly important to place the spillway upon rock, or the most solid portion of the undisturbed ground protecting this with pavement of rock or concrete in such way as to prevent cutting.

The type of spillway is governed by the topography of the country. It is usually possible to find a depression in the rim of a reservoir which may be enlarged or modified in such form as to provide a lip or sill of several hundred feet in length. In some cases, as that at the Shoshone Dam, Wyoming, where the works are in a narrow canyon with almost vertical walls, it has been necessary to provide a spillway discharging through a tunnel around the end of the dam. It was not considered safe to allow the water to pour over the top of this structure 327 ft. high. In this case, a large funnel-shaped opening has been provided with a broad curved lip, 15 ft. below the top of the dam, the water pouring over this lip falls into a depression in which it converges to enter the tunnel where with a velocity of upward of 20 ft. per second it passes through the opening in granite walls out well below the toe of the dam.

Grades and Velocities.—In every spillway device the object is to take the water away as rapidly as possible, consistent with safety, and therefore the maximum allowable grades should be provided, so as to reduce the size of the channel to be made. If the discharge is over a granite or similar hard rock, the spillway may consist of a series of falls or rapids. If through softer materials such as shale, it may be necessary to line the channel with concrete and reduce the grade to prevent the excessive velocities wearing out the lining. As a rule, the large spillways are only called into use once or twice a year, or perhaps only once in a decade, and then for only a few hours or days, so that such erosive forces are not indefinitely continued. It is therefore, practicable to take larger chances on erosion than would be the case with structures in continuous use, that is to say, after a large flood there will usually be an interval of months of even years during which any small damages may be repaired, so that it is perfectly proper to assume the probability of small injuries. On the other hand, it is extremely dangerous to incur any risk which may take place during a large flood, creating an injury sufficient to disturb the structure and to release the stored water behind the spillway.

Protection against Erosion.—The most effective protection against erosion is by suitably placed masses of masonry or lining of concrete as shown on Plate XVI, Figs. C and D. In some cases, logs or timber may be used to protect the softer rocks or points of weakness, as this timber, although it may be warped by the sun, will afford enough protection during the short duration of flood to prevent injurious action.

The concrete lining of a spillway section may be dispensed with in part by building a series of drops or pools, although it is generally found to be more economical to line an inclined chute with a relatively thin mass of concrete than to attempt to concentrate the fall in a few places by using heavy structures.

CHAPTER XVIII

WATER RIGHTS

Definition.—A water right may be described as the ownership or claim which has been sustained by the courts or some form of action by suitable state officials by which there has been established the right to the use of a certain quantity of water. This is usually limited by seasons or periods of the year, that is to say, the right to the use of water taken from the common stock, is limited not only in quantity, but also in duration, being as a rule confined to the crop-growing season. There are, however, water rights out of the crop season which may be utilized for purposes of storage in reservoirs and in some cases the claims are made that the rights are to possession of a continuous flow of water at all times, irrespective of the season.

The term water right is often used loosely to imply simply the claim to the right to use water and not to the actual established right. For example, it may be said that a certain water right includes the entire flow of a given stream, meaning by this that the claim is made that the entire flow belongs to or is appurtenant to certain described tracts of land. The distinction should be made, however, between the actual rights as properly established or confirmed and those which are more or less vague and arising simply from notices posted or entered upon the county or state records and which have not ripened by process of law into actual rights.

The engineer having determined from the physical standpoint that there is an adequate supply of water for the proposed irrigation works, must give careful consideration to the question as to whether the rights to the use and control of this water have been or can be properly guarded. Many an engineering work otherwise successful has been a failure because of neglect of this precaution, as, for example, where an engineer has made his plans with reference to the given volume of water which he has found to exist, but, to his astonishment, has later found that the title to this has been so insecure that his works have never been able to operate successfully.

The legal and engineering questions relating to water rights merge in such way as to be practically inseparable. This is because of the fact that water occurring in nature in fluctuating volumes is not susceptible of exact limitation by metes and bounds, as is real estate and it is not possible to establish accurate lines of division in the same way that farm boundaries can be laid out upon the ground. In the case of a stream which on one day is carrying 300 second-feet and on another 30,000 second-feet, and on which the claims to the water at the various points along its course may aggregate 1,000 second-feet, the problem of exact limitation of the quantity available to each of several hundred claimants is a mixture of physical and legal problems which can be solved only by the engineer and lawyer working together, each having a fair comprehension of the technical requirements of the other.

The proper acquirement of the rights to the use of water and the perpetual protection of these are among the most vital points in the planning of any irrigation project or system. While it is not to be supposed that the engineer or businessman having to do with irrigation works is fully versed in the details of irrigation law, yet it is necessary that he have such knowledge of the fundamental facts and sufficient grasp of the general principles to be reasonably certain that the rights involved are adequate. At least, he should have such general knowledge of the dangers as will lead him to call for the best procurable legal advice upon the points involved.

The method of determination of the rights to the use of water and the operations or practices are by no means uniform nor certain. The whole subject of water law as pertaining to irrigation is still in a state of evolution and every important point should be thoroughly questioned and carefully considered in advance of entering upon any new scheme.

There is great apparent contradiction in court decisions on fundamentals and their application, so that no important point should be assumed as established until thoroughly examined and passed upon by competent authorities.

Origin of Water Rights in the United States.—Water rights in the arid western states of the Union are derived primarily from the original federal ownership or authority, as nearly all of the arid lands formerly belonged to the United States. These lands have been or still are at the disposal of Congress and for the most part are open to settlement under the homestead laws. With the ownership of the arid land was included also the ownership of the waters originating in the mountains or elevated plateaus of the national domain.

One of the conditions attached to the disposition of the arid areas, notably under the terms of the Desert Land Act, is to the effect that they must be reclaimed by the use of waters taken from the streams, and applied to the soil, the water thus taken not being returned to the water course.

This requirement of taking water from the rivers enacted into law by Congress, is a recognition of the common need of the country of the diversion of the streams to irrigate the arid lands. It also illustrates the fact that the riparian ownership of water as embodied in the common law of England and in the statutes of the eastern states is not applicable to the needs of the people of the arid regions.

Under the theory of riparian rights each owner along the natural stream enjoys the right to have this stream flow in its natural state practically undiminished in quantity, and unchanged in quality. This is in accordance with the common necessities of a humid region where there is usually water in excess and where no one man should be allowed to interfere with the natural behavior of the stream to the detriment of his neighbors.

In the arid region, however, this "let alone" policy is obviously impracticable. The lands cannot be put to their best uses without taking water from the stream. This water, if put to beneficial use, cannot be returned to the stream, and hence the flow of rivers must be systematically diminished and finally the beds will become nearly if not quite depleted if the arid region is to be reclaimed. The time is rapidly approaching when in the lower courses of the natural streams there should be no water left, excepting possibly in times of unusual floods. If water is thus found, it may be considered as an indication of poor management or imperfect control of the natural resources of the area.

The generally accepted theory that water in a natural stream is the property of all of the people is based on the fundamental fact that it is essential to all life, both animal and vegetal. In distinction to natural streams, however, are the waters which occur in springs or wells upon certain tracts of land and which are considered as belonging to the owner of that particular tract of land. With the proprietorship in springs may be classed also certain waters taken from a natural stream and put in an artificial reservoir. When thus severed from the common ownership such waters become the property of the owner of this reservoir, and are no longer subject to the rules governing flowing waters.

In some of the western states, the claim is occasionally made that the natural waters belong not to the people but to the state and that the state may dispose of these waters in accordance with law. But, it is more generally held that the control of the state arises not through actual ownership, but through other powers. It is universally recognized that the state must have such direct control over the distribution of the waters to the claimants as will insure an orderly use of these and prevent discord.

As there is not sufficient water in the arid region for all purposes, the great question next to that of ownership is as to who shall take from the common stock and who must be denied the water which is necessary for life and for crop production. A rule generally recognized is that of first in time is first in right, but this must again be modified by other considerations, as the first man who takes the water may desire to use it in ways not wholly in accordance with the common good. Thus have arisen the superior claims for water needed for the sustenance of life, that is, for domestic purposes, for cattle, and for municipalities as being prior to all others. Next comes agriculture, or the needs of crops produced for food to sustain life, then manufacturing or industrial purposes, as less important than the fundamentals of drink and food.

Having settled that priority of appropriation and use shall govern and that within these priorities there are certain superior needs, the next broad question is that connected with considerations of waste of water. On this point, the most generally accepted rule is that which has been incorporated in the Reclamation or Newlands Act of June 17, 1902, which states "that the right to the use of water acquired under the provisions of this act shall be appurtenant to the land irrigated and beneficial use shall be the basis, the measure, and the limit of the right." This embodies two distinct and fundamental ideas vital to the proper use of the common fund of water. First, of appurtenance to the lands irrigated, and second, of beneficial use.

The appurtenance to the lands irrigated means that when water has been appropriated for a certain tract of land, the water needed for this land goes with it and is not held separately in a way such that the land may be deprived at some future time of the necessary supply. The importance of this principle is not dependent wholly upon the need of the particular tract of land under consideration, but is in recognition of the fact that other rights grow up in time such that if water is not used upon this particular piece of land, but should be transferred elsewhere, confusion would ensue with a consequent loss directly or indirectly to other lands.

The second and perhaps more important rule is that of beneficial use. Usually, the law does not attempt to state in engineering terms how much water shall be used on any tract of land, but limits this by the broad definition of beneficial use. At first, a certain 40-acre tract may require a large amount of water, while the subsoil is being filled and the surface subdued or filled with humus. At a later time, with increase of irrigation in the vicinity and with the changes which follow, a very small amount of water may be applied to the surface and sometimes none at all throughout an entire crop season. The rule of beneficial use works automatically in that, if water is not actually needed for this particular tract, none may be successfully claimed.

Riparian Rights.—Under the term riparian rights are included those claims to adjacent waters established by usage or by judicial processes under which the owners of land adjoining a stream enjoyed the direct or indirect use of these waters. These riparian rights are generally limited in such way that the abutting landowner may take some of the water for domestic use or for cattle or for manufacturing and other industrial purposes but his rights are limited by those of the entire community. These usually require that the water be left practically undiminished in quantity and unpolluted or otherwise changed in quality.

The doctrine of appropriation and priority of use has been generally adopted throughout the arid part of the United States. This is in direct opposition to the principles governing flowing water which are embodied in the laws and court decisions of the eastern or humid states. Within these the so-called riparian rights prevail, being adopted from English practice.

Riparian rights are founded upon the theory that there is enough water for every ordinary purpose and to spare, and that the flowing water cannot be diverted to the exclusive use of any one, excepting as far as ownership of the lands along the banks may permit such diversions. Each landed appropriator bordering upon a stream must permit the flow to continue practically undiminished in quantity and quality. He may take it out upon his own land, but he must return it after having put the water to use for power, or for other purposes. The enforcement of any such doctrine is, of course, directly antagonistic to the common needs of the people of the arid region where the lands have little if any value excepting by the use of the water taken from the streams.

The riparian law was founded upon the common needs of the people of a humid region. It was the outgrowth of practical or common sense as applied to the daily problems. In England it has been modified from time to time according to the conditions of development of the country and the larger needs of the people but in the humid parts of the United States, the riparian doctrine has become so crystallized into law and so rigid in application that to a large extent it has not been conducive to the largest possible development of water.

In the arid regions the riparian rules are not wholly applicable, as there the common needs of the people are dependent upon taking water away from the stream, using it and returning little, if any, to the natural drainage. On the extreme western border in California, a state partly humid, the system of laws originally adopted by the Americans were copied from those of the eastern humid states and included the ideas of riparian rights. In the arid portion of the state, however, especially near the old Missions, there grew up in accordance with the needs of the people, the recognition of the Spanish theory of appropriation and use of waters. Thus these two antagonistic principles came into conflict as the state was developed. The result has been innumerable controversies and court decisions which at one time appear to favor riparian rights, and at another the necessary rules of appropriation. Neither has yet been definitely and conclusively established as against the other, but there appears to be a tendency to interpret the riparian rights in accordance with beneficial use, that is to say, if a riparian appropirator has put the water of a stream to beneficial use either for watering his cattle or for irrigating his land, he will be protected in this, but he may not neglect to use the water indefinitely and then at some future time demand his riparian rights to the destruction of valuable improvements and irrigated lands above or below him.

It is essential that the engineer in planning his works know something of the extent of the riparian rights which may be claimed upon the streams. He should receive definite assurance that such rights do not exist, or are limited and that he may depend upon the rules of appropriation for the water supply needed for success.

Acquisition of Water Rights.—Starting with the proposition that the Federal Government permits and requires the diversion of streams on the public domain for reclaiming desert lands, as a requisite to obtaining title to these, it has followed that as new states are created within the arid regions and duties of providing systematic methods of administration are prescribed, these newer states of necessity have been forced to consider the orderly distribution of the waters and the adoption of certain broad fundamental rules. As previously noted, in most of the state constitutions of the arid region, it is recognized that the waters belong to the people. In some of the states the phrase is used in such a sense as to imply that they belong to the state but this ownership by the state is obviously not the character of ownership by which the state may sell or dispose of these waters or deal in them as it might in lands or buildings.

Assuming as true, the fundamental proposition that the waters belong to the people, next comes the recognition of the fact that as there is not enough water for all of the people and there must be some orderly system for distributing these and for giving to certain persons an exclusive right or an artificial monopoly. This is generally done in accordance with the rule that a man first in time is first in right. If the first-comer should claim everything in sight there will be nothing left for the next man. It follows that it is necessary to modify this rule by another, namely, that the man first in time shall be limited to an amount of water which he put to beneficial use. Otherwise, he might file claims, as many pioneers have done, to the entire flow of the river, proceed to divert a small percentage of it and try to hold the rest for speculation profit.

In determining officially the amount to which each claimant is entitled, it is necessary for him to show that he put the water to beneficial use to a certain extent prior to a certain date, or to the time when others also utilized portions of the water. This is embodied as before pointed out in the latter part of the provision in the Reclamation Act to the effect that "the right to the use of water shall be appurtenant to the land irrigated, and beneficial use shall be the basis, the measure, and the limit of the right."

The methods of acquiring water rights are variable; each of the states has its own system or lack of system in the matter. In general, it may be said that all of the states recognize rights as acquired by actual construction of works and by the application of the water to the land or by exercising due diligence in making such application of the water. In some of the states a regular system is provided, namely, of applying to a state official, usually the state engineer, for permission to divert a certain stated amount of water for irrigation for a definite tract of land. It is supposed to be the duty of this official to ascertain whether there is actually water available for appropriation. To do this he takes into consideration what is known of the flow of the stream and of the appropriations already made. If he is satisfied that there is water which as yet has not been appropriated, a permit is issued. If work is pursued with diligence and proof is made of actual reclamation, the right then becomes established.

In case of shortage the prior appropriators receive their full supply, and the later appropriators receive what is left, each in the order of the date of the official records.

In other states, where an orderly or business-like system has not been developed, it is customary to post notices of appropriation along a stream or at the point of proposed diversion of the water, and to make this notice a matter of record within the county. Thus, as developments proceed to a point where there is scarcity of water and controversies arise, it is necessary to bring the whole matter into court, and to settle relative rights according to the testimony of the older inhabitants.

This has proved an expensive and dilatory process and in some counties it has been asserted that the expenses of litigation are greater than those of construction. For example, "A" may bring suit against "B" to settle their relative priorities, and "B" against "C," and so on, with infinite combinations, and when all have been exhausted some successors to older and apparently abandond claims X, Y, or Z, may bring suits individually or against collective groups, and get the whole matter again into court. Wherever practicable, the attempt is now made to include in one suit all of the possible claims on the river and its tributaries, and in some instances in order to settle relative rights, suit has been brought against upward of 4,000 individuals.

The recognition of the necessity of an orderly and systematic procedure in establishing rights to the use of water has not yet reached the point of completeness in the United States comparable to that attained with reference to land titles. While great care is exercised in verifying every point with reference to title to a farm, there still exists a relatively chaotic condition with reference to the water which in many localities alone gives value to this land. We are still in many parts of the country in what may be called a medieval condition as regards titles to water, one where each man claims everything in sight and the aggregate of the claims exceeds by many times the amount of water available. With the rapid development of a higher standard of public or civic morals must come the recognition of the necessity of simple and comprehensive methods of securing titles to the use of the flowing waters.

While there is great uncertainty in these matters, and caution must be used, yet this uncertainty is not such as should deter legitimate investment, for it has been shown that good faith in the construction of works which are adequate to hold and distribute the water supply, followed by continuous beneficial application has usually been sufficient to constitute an appropriation which will be sustained in legal controversies. In the majority of the cases where water is available and men have proceeded in good faith to utilize it, and have done so, the probability is that they may continue in this without molestation.

Theory Upon Which Granted.—As stated in previous paragraphs, the theory upon which the right to the use of water is granted by the state or confirmed by the courts is that of beneficial use in the order of priority of appropriation, or of time in which this has been put to such beneficial use. The man who first builds a canal from a stream and utilizes it is almost invariably protected in such use and to the extent to which he has beneficially applied it, as against all subsequent appropriators, especially if he has endeavored to make record of this fact in the proper place with the county or state authorities.

On nearly every stream notices have been posted at various points claiming a thousand miner's inches or any other large quantity. The amount claimed is usually some figure or phrase which appeals to the fancy of the would-be appropriator rather than applicable to the physical facts. Relatively few of these early claimants had any conception as to what was the volume of a miner's inch or of a cubic-foot per second, hence their filings have been for a volume sometimes exceeding that of the stream, or even by mistake for an amount so small as to be insignificant. Adding these claims, the total is sometimes ten times that of the flood flow. In attempting to apply these claims, however, the basis of recognition of appropriation has been not as to the quantity which has been claimed but upon the amount which has been or is actually being used, as shown by the size of the canal and the number of acres irrigated.

For example, the early appropriator in his ignorance of quantities of waters may have filed upon 10,000 miner's inches, or 200 second-feet. His canal as first constructed may have carried 10 second-feet and may have been enlarged to 20 second-feet. If he has shown due diligence in this enlargement it is probable that when the matter comes to final determination, he may be given a priority of 20 second-feet, dating from his original notice, or he may be awarded 10 second-feet, as a first priority, and an additional 10 second-feet to cover the enlargement, this later amount being subsequent to the claims of some other appropriator. If there are, say, 100 such appropriators along a stream, and each has made enlargements at different times, it is easy to see how complicated the official adjudication of water must be where the fact must be established as to the relative dates at which each important enlargement of the various canals has been made.

Beneficial Use of Water.—The principal fact to be established beyond the date of original appropriation and construction is the fact that the water has been put to beneficial use. The mere statement that the original claim was initiated at a given time has relatively little force as any one may have claimed the waters of an entire river by simply posting notices to this effect. The vital test must be as to whether the claimant actually took the water from the stream and used it beneficially, not wasting it nor trying to hold it for speculative purposes.

Unless the test of beneficial use is applied, it is easy to create a monopoly of this great necessity of life. A man might lay claim to the waters of many streams and in this way, although owning little, if any, land, be able to levy tribute upon every industry and even upon life itself within the district. Such condition is repugnant to public welfare and hence there has arisen naturally the simple rule that each claimant must prove beneficial use and, having made proof, he should be protected in the continued use until abandonment of it has been shown.

Beneficial use of water for irrigation may be defined as such application of the water as will result in prolongation of life, animal or vegetal, and in the increased value of crops or in the production of power necessary in various industries. While any general definition is necessarily vague, yet in each specific case it is usually easy to determine whether the water has been put to beneficial use by an examination of the facts. It is peculiarly the duty of the engineer in connection with those of the lawyer, in considering the relative rights to water, to make the measurements and deductions which establish the actual facts. For example, a canal constructed to carry 100 second-feet and taking water to 1,000 acres cannot be considered to have a proper claim to its entire capacity for beneficial use, as this amount of water should be sufficient for 10,000 acres.

On the other hand, a canal of 10 second-feet capacity which is claimed to irrigate 10,000 acres cannot form the basis for a claim to sufficient water for this 10,000 acres because it is obvious that the water could not be delivered through such a canal, its capacity being entirely too small. Thus, the determination of beneficial use in any particular case or groups of cases is one of fact which can be determined only upon the ground and established by the testimony of competent men.

Water Rights Apart from Lands.—Under the theory which is generally accepted as correct throughout the greater part of the arid region, there cannot be nor should there be any such thing as right to flowing water independent of ownership of certain tracts of land. In other words, public policy demands that each water right shall be appurtenant to a certain specific tract of land upon which the water may be put to beneficial use. Unfortunately, however, there has grown up in some of the states and been recognized by the courts a theory that the right to the use of water may be of the nature of personal property transferable from one locality to another, that is to say a man may own in a certain stream enough water to irrigate 100 acres. He may rent this to a neighbor one year and take it away and rent it to another for the next year. The objection to this is that such ownership is not consistent with the public welfare. It enables the establishment of a landlordism, repugnant to the popular institutions, as it enables one man to absolutely control the source of life for a large district.

To illustrate this point, may be taken the extreme case where in medieval times certain authorities claimed the exclusive right to the air over certain districts and endeavored to enforce taxes or tribute upon the use of the air!

The idea of ownership of water apart from the land has grown up through ownership in the shares of stock of a partnership, coöperative agreement, or corporation, which has built a system of irrigation. For example, a half dozen farmers owning certain lands agree among themselves to build a canal to irrigate these lands. They do not have sufficient cash capital and must purchase materials or hire additional help, so a capitalist joins with them with the understanding that he shall own a proportional part of the carrying capacity of the canal. Thus, the farmers obtain the waters for their own lands or for a part of them and from year to year rent from their associate who has furnished the capital, the use of the additional capacity of the canal.

This is a proper and legitimate conception as far as the use of the canal is concerned, but it is easy to pass from this rental of the use of the canal to the assumption of the ownership of the water which is taken into the canal. A careful distinction should be drawn between these two. It may be possible and proper to recognize that the water in the canal is appurtenant to the tracts upon which it is used. The persons owning this land may be required to pay a tax or license for the transportation of the water by means of the canal to the lands to which the waters are appurtenant. This is far different in outcome to the proposition that the water is owned by the proprietors of the canal which transports it. As before stated, this claim of ownership of the water by the canal owners has been recognized in some states, but the tendency is to acknowledge the right to carriage only and the right to collect dues as by a common carrier but not as a right of ownership of the flowing water apart from the land.

CHAPTER XIX

ECONOMIC FEATURES OF IRRIGATION

Feasibility of Irrigation.—After all of the detailed studies and examinations have been made of the engineering, legal and related features of any proposed enterprise, then it becomes necessary to study the whole project from the broad standpoint of its feasibility. It is assumed as a matter of course that before starting any detailed investigation, its feasibility is known to be more than probable. As a result of careful studies, this question of feasibility must be practically determined before entering upon expensive construction.

The prime consideration as regards feasibility is based upon the probable financial outcome. In other words, will the enterprise pay? This is true not only from the individual or corporate standpoint, but also from that of the state or nation. The financial reward in the two cases may be estimated on a different basis, that is to say, the individual or corporation considers the financial aspect with reference to direct profits to be attained, while the state may consider indirect sources of profit that resulting from a prosperous taxpaying citizenship.

In either instance, the consideration of feasibility can best be reduced to the easily understood expressions of dollars and cents. This is the measuring stick which must ultimately be applied to all proposed enterprises.

In turn, the question of financial profit rests upon an infinite variety of conditions such as have been touched upon in the preceding pages. These may be grouped under the two general headings of, first, physical difficulties, and, second, obstacles of human origin. The first lie directly within the cognizance of the engineer, the second, and the far more important and difficult, lie only partly within his technical skill, the remainder being largely within the domain of the lawyer or specialist in various lines.

Fundamental Questions to be Considered.—Of the physical questions to be answered, the first and most important is usually that of water supply. Throughout the arid region as a rule, there is more good land than there is water, and the chief limitations as before stated rest upon facts as to whether sufficient water can be had each year to cover a given area of land. This matter being determined, the next in order is as to the extent and character of the land, and its location with reference to the water supply. The quality of the water should also be given thought as in many parts of the west, especially during low water, the streams carry a very large amount of earthy salts in solution, and in times of flood, great quantities of silt, which tends to choke the canals.

The human obstacles to which reference has been made are those surrounding the control of the water, or protection of the rights to the continued use of the flowing streams, also those growing out of questions of rights of way for structures and of the relation of the management of the canal system to the irrigators upon whose success as farmers depends the ultimate outcome of the investment.

Value of Land.—The profits to be made from any irrigation development lie not in sale of the water but in the increased value of the lands which are served. This simple fact has frequently been overlooked and as a result many irrigation investments have been financial failures. There has been too much dependence upon the assumed profits to be made out of the sale of water rights or out of the operation of water supply system, but, as a matter of fact, it has been found that the only profits derived are those from the increased value of the land. Assuming that the soil is adapted for agriculture, as it is throughout the greater part of the arid region, the lands without water may be considered as having little or no value in their native state, hardly more than the cost of conveyancing. With water they have a large potential value, or will pay a large rate of interest when developed, upon an investment of $100 to $500 or more per acre. The cost of bringing water to these lands may be assumed to be $40 an acre and the increase in land values may be several times this cost of providing water.

This gain in value of land from nothing to $100 an acre or more goes not to the builders of the canal system, but to the owners of the land. If these are the same persons, then the investment may be a financial success, but if one set of men build the works and another set own the land, the profits, whatever they may be, almost invariably go to the landowners. The investors in the irrigation works as distinguished from landowners as shown by past history, have almost without exception lost their investment. It is not necessary at this time to trace out the reasons why this has occurred, but as a historic fact, this may be stated. The men who have put their money and time into the construction of irrigation works have been "involuntary philanthropists" in that they have developed a country and made possible the creation of wealth for others, but have not been able to bring to themselves a fair share of the reward.

Increase in Value.—The moment that an irrigation system is projected, there attaches to the land which may be covered a speculative value and the selling price may jump from the government rate of $1.25 per acre up to $5 or $10 per acre, on the assumption of early construction of the project. As the works advance, this speculative value becomes more and more inflated, until the time arrives when it becomes necessary for the owners of the land to begin to repay a part of the money invested in the irrigation works. Then there is usually a sharp decline in land prices. This is because of the realization of the fact that payments must be met and also a better appreciation of the pioneer conditions, namely, that a considerable amount of labor and money must be invested in subduing the soil to get it into good productive capacity, or tilth.

In the more northern states where the crop season is limited to the summer months and where two or possibly three cuttings of alfalfa can be had, the lands as they are brought to a condition of tilth steadily increase in selling price. This may go up to $100 to $150 per acre, dependent upon the degree of care shown in levelling the fields for irrigation and in fertilizing the soil to bring it into the best agricultural condition.

There is a common fallacy in the statement that the soils of the arid region do not require enrichment, but that the irrigation water supplies all needs. This is far from true, for, although the desert soils frequently contain earthy salts of value to plant life they are usually deficient in nitrogen and frequently in phosphates. The nitrogen can be supplied by cultivating alfalfa, clover, or plants of related families, occasionally turning the green plants under by plow, so as to put the organic matter into the soil, but the phosphates, if needed, must be brought in from other areas.

In the more southern region, with warmer climates, especially where fruits can be grown, or where the number of cuttings of alfalfa may be increased, the land values are correspondingly larger. When the ground has been properly tilled and young orchards set out, the values reach into hundreds of dollars per acre. Much of this value is given by the labor which has been spent upon the farm, but a considerable portion is what may be called the unearned increment of value, due to the bringing in of the water.

This increase in land value is several times the first cost of the water, because of the fact that the control of the water is practically a monopoly, there being usually not enough water for all of the good lands. The profits to be obtained are thus those which attach to the creation of a monopoly, and these come, as before stated, not to the builders and owners of the canal system, which transports the water, but to the owners of the land to which the water must necessarily be appurtenant. The failure to recognize this simple but fundamental fact has led to many failures in financing irrigation enterprises.

Soil, Climate, and Crops.—In all considerations of reclamation schemes due attention should be given to the character of soil, to the climatic conditions, and to the possibility of producing certain classes of valuable crops. It is true that these matters are of less immediate importance than those of water supply, because of the fact that taking the arid region as a whole, the soil is usually well adapted to agriculture and the climatic conditions are generally favorable to the production of some kind of crop, but because these matters are secondary they should not be overlooked.

Most of the soils, especially of the desert areas are somewhat sandy, light, and easily tilled. In the lower valleys, however, there are frequently large areas of clay or adobe which require much more careful manipulation for success. Each class of soil presents its peculiar conditions and problems and requires intelligently directed efforts.

Fortunately, there have been established throughout the arid regions experimental stations where careful observations have been and are being made as to the results of different methods of treatment and the agricultural colleges are diffusing information as to peculiar conditions to be met. A book, or in fact many volumes, might properly be devoted to the subject of soils in their relation to irrigation, but it is sufficient in the present connection to call attention to this fact, and to the necessity of having an expert examination of the soils which it is proposed to irrigate, in order to determine in a broad way the fundamental questions as to the amount of water which may be needed and especially the probable behavior with respect to necessity for drainage.

As regards climate in its relation to irrigation, it may be said that irrigation is most beneficial and is absolutely necessary where there are droughts prevailing through a whole or part of the crop season, which is usually the case where the rainfall throughout the year is less than 10 to 15 in. in depth. A small amount of rainfall means as a rule a large amount of sunshine. As the sun is the source of all life and growth, it follows that with an artificial supply of moisture in these regions where the sun shines nearly every day, the plant growth must be rapid, even though during much of the year the climate is notably cold. It is a matter of surprise to note how successful irrigation is, for example, in portions of Canada where, taking the year through, there is a very cold climate. The summer season though short is notable for its long hot days. Where water can be applied, the plant development during this short summer is extremely vigorous, thus it results that irrigation is being extended into the Canadian northwest; to a country which is popularly supposed to have an almost artic climate but which actually produces notably large crops during the short, intense, summer period.

The largest success under irrigation is attained, of course, in the truly desert areas of the southwest, where the climate is such that plant growth continues throughout the winter season with a very short period, if any, of rest. Here crop follows crop in rapid succession; alfalfa, for example, can be cut at intervals of five or six weeks, and field crops may be had in rapid rotation, sometimes three cultivations on the same ground being successful during each calendar year.

With respect to the crops which may be raised, this is a matter which must be governed not only by the character of the soil but very largely by human conditions, namely, those of transportation and market. In attempting to develop any new area, it is to be assumed that transportation has not yet been fully provided, and the question to be given serious consideration is as to the probability of early construction or improvement of railroads, and other means of taking the crops directly to the centers of population.

In some localities there may be in existence a local demand for crops such as that at mining camps in the mountains. In others, there may be need of forage for winter feed and for cattle upon the open range. For most localities crops should be selected in accordance with the means of getting these to the cities and towns and of selling them in competition with similar products from other producing areas.

It is a common mistake, especially in pioneer communities, to attempt the raising of varieties of crops which have been successful elsewhere, but which are not adapted to the peculiar conditions. The farmers coming from other localities naturally try to utilize the results of former experience, and do not realize that this experience is inapplicable to the new home.

Many farmers, for example, have been successful in raising grain by the ordinary or dry-farming methods and do not appreciate that the cost of irrigation does not justify continuing in this line. They do not keep sufficiently accurate accounts to know where their losses are occurring, and may keep on year after year planting those crops which are not netting them a sufficient amount to be remunerative. It is this failure to appreciate the relative cost and values of various crops which has led to the lack of success and relatively low crop values throughout a considerable part of the arid regions.

Permanence of Water Supply.—All values rest upon the water supply. The permanence of this supply, as previously noted, must be looked into not merely from the physical side, but even more carefully from the legal, in order to have proper assurance that if water is found to be in existence the right to the use of it may be perpetually maintained. The permanence from the physical standpoint is a matter which may be inferred only from an examination of records of the past. The assumption is made that whatever has occurred in the past will probably occur again in the future. It is necessary, therefore, to obtain every possible fact concerning the behavior of the stream from which water is to be obtained and of similar streams having like conditions. If, for example, it has been found through observations carried on during ten years, that the average flow during the summer is 1,000 cu. ft. per second, it is assumed that this average will be maintained for another ten years.

If there has been a large flood upon this or upon a similar stream, provision must be made for passing such flood and even a larger one around the works. On the other hand, if a drought has occurred allowance must be made for a similar drought with the possibilities that it may be somewhat more severe.

Provision must be made for all of these conditions based upon the fundamental conception that nature repeats itself. Our knowledge is, of course, confined wholly to what has happened in the past; we make all plans and investments upon the assumption of the permanency of natural phenomena. It may be that the period during which observations have been made is abnormal, that is to say, that for the ten years of observation, there may be more or less available water than has occurred in previous decades of which we have no exact records. This is the chance which must be taken, but experience has shown that by allowing a reasonable margin for safety, works may be planned and built upon these assumptions.

Cost of Constructing Works.—The cost of constructing works is the next topic in order after considering the questions of feasibility as regards water supply, soil, climate, and crops. It has come to be an axiom that this cost is generally greater than the original estimate. This is due not so much to lack of care and thoroughness in preparing estimates as to the fact that the work is pioneer in its character, and improvements are suggested or new needs arise so rapidly that works which were planned in one year as adequate for the purpose in mind are found to be unsuited or undesirable by the time construction is well advanced. Many changes must be made, or additional details provided which were not known or not considered necessary in the original scheme. It is, of course, possible that an engineer may plan works and build them exactly as planned and within the original estimates, but this condition is one which with existing irrigation systems does not take place under ordinary circumstances.

The engineer may plan for certain works to meet the then prevailing conceptions, but the owners or financiers usually conclude that it is necessary to add certain extensions or modify details such, for example, as increasing the size of the reservoir, or of the main canal, or adding a pumping plant. Thus, as a result the works cost more than anticipated, and, comparing the original statements of cost with the actual expenditures made it is seen that the latter are far in excess of the estimates, but the reasons for this are rarely given.

Men's ideas with reference to limits of practicability or cost of the works have rapidly expanded. The small canals built before 1900 were cheaply executed, the structures were of wood and of temporary character. The location was made with reference to keeping the construction cost to the minimum and much of the work was done by the farmers themselves, no account being taken of what is generally termed the overhead cost including that of planning and organization of the work.

At the same time, the estimates of the area watered were very liberally made. If some water was provided for a farm, it was habitually stated that the entire area say of 160 acres was under irrigation, even though water had only been as a matter of fact applied to a portion of it. The capacity of the canal might not be enough to supply all of the lands which were claimed to be irrigated. For these reasons the cost per acre of irrigation was stated at an extremely low price, less than $15 per acre. Beginning about the year 1900, a cost of $20 per acre for irrigation was considered high, but when it began to be appreciated that the land with a sure water supply would yield a large return on a value of $50 or even $100 per acre, it was recognized that larger investments in construction would be justified. Year by year the limits of assumed feasibility have been increased, so that by 1905, it was assumed that $30 per acre was large, then $40 per acre, and finally by 1910, a cost of reclamation of $60 per acre was not considered prohibitory, for lands especially in the southern part of the country. In fact, when consideration is had of the great value of orchard lands an expenditure of $100 or more per acre to provide water is feasible. In semitropical lands, for example, in the Hawaiian Island, where pumping plants have been erected for raising water for irrigation to a height of 550 ft., an outlay of several hundred dollars per acre is not considered out of the ordinary.

In the northern temperate regions, for example, in Colorado and Montana, for the ordinary field crops an investment of $40 to $60 per acre may be now considered as large but not prohibitory. This may be increased notably for warmer regions with longer crop season, such as those of southern Idaho, and portions of Oregon and Washington. Going south from here to points as in Arizona and California, where crops grow throughout the greater part of the year, an increase of 50 per cent. in the amount above named may be considered as moderate.

If estimates are based on the crop production of thoroughly irrigated lands it can readily be seen that these give a good income on an investment of from $200 to $500 per acre, so that theoretically, the figures above given could be increased several fold, but as a matter of fact, under existing conditions, it is hardly safe to figure on this basis, although it is possible to look forward to a time when far larger investments than now considered wise will be the rule rather than the exception.

Other Costs.—It must not be assumed that the cost of an irrigation system is simply that of the engineering or construction. There are other costs which may equal or exceed these and neglect of which in the preliminary estimates frequently leads to financial ruin. These are the somewhat vague and intangible expenses of the organization, the so-called overhead charges, especially of commission and interest upon bonds, or upon other securities issued for construction purposes. It is not infrequently the case that after the engineer has carefully estimated all of the construction cost and has allowed 15 per cent. or 20 per cent. for contingencies, the business man must double this to cover the items above noted.

Taking the ordinary conditions of private irrigation systems it may be said that assuming the engineer's estimate of construction at 100 per cent., the other items to be added will be about as follows:

Preliminary examinations, organization and promotion, 10 per cent.

General administrative, 10 per cent. This is after the funds have been raised, the general plans determined upon and construction carried to completion.

Interest on bond issue, 20 to 30 per cent. This is assumed to cover most of the construction cost, and is estimated at 6 per cent. per annum on the period required in the construction of large systems.

We thus have from 40 to 50 per cent. of the construction cost to be added at the time when the works are completed.

Beginning with the time of completion of the works and the beginning of active irrigation from then on is the period of greatest difficulty and stress. Settlement of the lands is usually slow, the farmers must experiment, the markets are to be established, and five, ten or more years may elapse before the land is completely irrigated and the farmers are able to make notable payments. During this time the cost of operation and maintenance has been large and this with the interest on bonds or other securities may amount to 75 per cent. or even 100 per cent. of the actual construction cost.

Markets and Transportation Facilities.—As before stated, the question of markets and of transportation facilities must be considered in any irrigation scheme. These are not usually at hand when the project is under consideration, but come as a natural outgrowth of the development of irrigation. As soon as it is apparent that products of the soil are to be handled in quantity, there is aroused an interest in the matter on the part of transportation agencies and markets are created in accordance with the products available. It is necessary, therefore, to place large reliance upon these future developments.

Any considerable area of desert land, say 50,000 acres more or less to be brought under cultivation, will attract railroad builders and one or more railroads will naturally be built into the territory as soon as the success of the works is assured. There is, of course, an element of uncertainty in this matter, but it is sufficient to call attention to the fact that it is not possible in advance of construction to be sure of railroads and markets and a certain amount of chance may properly be assumed, and in fact is always assumed, in the building of these works of reclamation.

The success of the farmer and his consequent ability to repay the building cost of the works and the expense of operation and maintenance, are, of course, dependent upon his ability to dispose of the crops. On the other hand, there is a certain amount of elasticity in that the crops can be varied from year to year to suit the changing conditions. If, for example, at first there are no railroad facilities, he can raise forage crops which are, as a rule, eagerly sought by the stockmen, and if prices are sufficiently low, cattle and sheep will be driven into the region for winter feeding or fattening. As transportation facilities improve, crops can be produced which may be shipped and higher and higher grades of perishable fruits can be produced.

Security of Investment.—All of these considerations of feasibility or practicability lead up to the point vital to the investor, namely, as to whether the money spent in the construction of irrigation works will be returned within reasonable time, with reasonable profit, and reasonable interest. In general, it may be said that investments in irrigation works properly planned with reference to adequate water supply and climatic and other conditions should be safe and profitable. Assuming that care and intelligence have been displayed in guarding the rights to the water, in planning and building the works, and in adapting them to the peculiar conditions, there is nothing which should be on a similar financial basis, because of the large annual profits which may be derived by the farmers from intelligently tilling the soil.

Under the above assumptions, the security and the value of the works to the community is beyond question, as they are vital not merely to production of crops but to the maintenance of population and even to the sustenance of life itself. As to whether they will be profitable or not, this is another matter. It has already been stated that the speculative profits or those growing out of the increase in values comes to the owner of the lands rather than to the builders or owners of the water-supply system as distinguished from the landowners. The fact that most irrigation projects as such have not been financially successful, does not reflect upon the value of the investment, but rather upon the lack of experience, skill and good judgment in planning and building and operating the works. To illustrate the point in mind, the irrigation works may be compared to the foundations of a building. Upon them rests the whole social and economical superstructure. Their value and importance is beyond doubt, but like the foundations of a building they may return very little, if any, direct profits on the investment. These come from the superstructure itself, which is carried by the foundations. Of course, if they are poorly designed and imperfectly executed, everything built upon them is correspondingly weakened.

Summing up the entire consideration of economic features, it may be said that we are still in what may be termed the pioneer stage of development, particularly in the solution of the great problem of the proper relation of all these matters one to the other.

In each one of the separate details large experience has been had and it is possible to find a man skilled in engineering or in economics who can successfully handle each one of these questions or even several of them, but when it comes to the entire combination, few men, if any, have had the experience in all the parts needed to produce success. In other words, each separate part may be properly designed and operated but the whole assemblage may be a failure.

In this respect the situation is very similar to that in the organization of a large manufacturing establishment which has been initiated by men who have not been brought up in this particular line of business. It may be assumed that each one of a group of several experts is competent in his specialty; for example, one man in designing and installing the machinery, another man in the purchasing of raw material, another in selling, etc., but these men have never before been associated together and have not grown up with this particular combination. Thus, we have the condition where each part may be excellent in itself but the lack of cooperation or of so-called "team-play" prevents the success of the whole, although this lack of success is not attributable to the defect in any one operation. It is this condition which prevails on many of the large irrigation projects in that the whole assemblage of parts and their successful operation is still largely in the experimental stages.

Ultimate Results.—The engineer may derive satisfaction from his work in irrigation not only from the financial returns but from the consideration of the fact that these works have the largest direct bearing upon the material prosperity not only of individuals and communities, but of the state and nation. They form the foundations upon which are built agricultural communities, villages, lines of railroad, and the whole social fabric, embracing not only the farmers, but all of the trades and occupations which have to do with transporting or manufacturing the materials produced by the farmer, or designed for his needs.

The engineering works thus not only directly make opportunities for homes for the men who till the soil, but for every home thus created there is possibility of another home for the mechanic or artisan or railroad man who is engaged in supplying the needs of the farmer or in transporting the raw and manufactured products from or to the farm. To the investor also there is offered opportunity for not merely increasing his capital, if intelligently used, but of obtaining this increase through assisting other men to utilize the natural resources which otherwise go to waste. Finally, to the public man or statesman, there is no subject more fascinating or more important than that of watching and aiding in the development of the country through the intelligent conservation and use of these natural resources.

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