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UNDERGROUND-WATER PAPERS

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UNDERGROUND-WATER PAPERS, 1910.

INTRODUCTION.

By Walter C. Mendenhall.

This report is the fifth of a series of collections of short papers that give brief accounts of investigations of special underground-water problems by the United States Geological Survey. The first three of these, under the title "Contributions to Hydrology of Eastern United States," covering the years 1903, 1904, and 1905, were published as Water-Supply Papers 102, 110, and 145; the fourth, which was of the same scope, appeared as No. 160 of the same series under the title "Underground-Water Papers, 1906." The four earlier volumes were prepared under the direction of Myron L. Fuller, at that time in charge of ground-water investigations in the eastern United States. The report for 1910, like its predecessors, consists of a number of short papers giving the results of special or subordinate investigations, accounts of which are not considered sufficiently important to warrant their separate publication. Most of these papers also were prepared under Mr. Fuller's direction.

In this report an attempt has been made to bring together and to discuss a number of peculiarities affecting the economic value of wells and the occurrence of water in certain special classes of rock of widespread occurrence. Most of the papers, though based on more or less local observations, deal with problems of wide application and are therefore of general as well as of local interest. In fact, the special endeavor in them has been to present scientific results that will be of interest to the geologist or engineer, the publications of the results of general investigations of the occurrence, availability, quality, and other features of the waters found over extensive areas—such as the various States and Territories and the larger artesian basins—being reserved for special reports.

DRAINAGE BY WELLS.

By Myron L. Fuller.

INTRODUCTION.

Necessity of drainage.—A certain amount of moisture is needed to grow and mature all useful plants, but too much may be nearly as bad as too little, and, except for a few plants (rice, for instance), good crops can not be had from saturated soils or from soils covered with standing water. Unfortunately many areas of our country are poorly drained. In the north are numerous swamps and lakes in depressions in deposits left by the glaciers which once covered the region; along the larger rivers are broad areas of swampy flood-plain deposits, and in the coastal plain regions of the Atlantic and Gulf States are the broad, flat, poorly-drained, and often swampy upland areas between the streams. Immense tracts of lands which have rich soils and which would, if drained, yield abundant crops, are in their present condition almost worthless. If such lands can be reclaimed they will add materially to the productiveness and prosperity of the country, so that their drainage is a problem of great importance. Some areas, such as parts of the Mississippi delta and some of its flood plains, can never be satisfactorily drained without pumping, owing to their slight elevation above the river or sea, but by far the larger part of the wet lands of the country may be drained by one or another process, although the drainage of some areas may be prohibited by the expense involved.

Methods of drainage.—Wet lands may be drained in several ways. The water may be collected in ditches and conducted by gravity to some stream. Subdrainage by tile pipe is similar in nature and results to ditching, but does not involve the loss of the space taken up by the ditches. Though tiling is laid underground, both tiling and ditching eventually carry the water away over the surface. Drainage wells, on the other hand, carry the surface water into the ground.

Ditching and tiling are the simplest methods of drainage and are employed on lands that are moderately flat, if they are not too far removed from a stream or valley capable of taking away the water and if they are not separated from the drainage lines by ridges of too great height. The wet lands of flood plains and the swampy upland crests between rivers in parts of the coastal-plain region are particularly susceptible to ditching, by which hundreds of thousands of acres have been reclaimed. The floating steam dredge, pushing its way through the swamps of the Mississippi and other bottom lands, is a common sight.

In the uneven glaciated regions of the northern United States, on the other hand, where confused belts of irregular knolls and ridges alternating with deep depressions occur over extensive areas, the conditions are very different. In such regions most of the areas to be reclaimed are covered by relatively small ponds or swamps, which must be drained by the individual farmer rather than the community. The drainage of these ponds by ditches is also limited to a few localities where streams to receive the water are near at hand and on the same property and where the divide through which the ditch must be cut is relatively low, conditions which, unfortunately, are not common, so that recourse must be had to some other method. The method most commonly adopted is to sink a well in such a position that it will receive the drainage of the pond or wet tract and conduct it to some porous bed of sand or gravel beneath the surface. Whether or not this is possible depends on local conditions at the point to be drained, the method being by no means generally applicable. Where the conditions are favorable, however, the method is effective, especially if only a few acres of marsh or pond are to be drained.

CONDITIONS OF DRAINAGE BY WELLS.

General ground-water level.—Wherever the surface materials or rocks are porous or contain joints, fissures, or other openings, a boring passing downward penetrates a zone saturated with water, the depth to which ranges from a few feet in regions of abundant rainfall, especially where the surface is relatively flat, to perhaps hundreds of feet in deserts or in upland plateaus and other elevations adjacent to deep valleys into which the water is drained. In the regions of abundant rainfall, in which alone drainage is commonly necessary, the top of this saturated zone, otherwise known as the water table, fluctuates with seasons, rising during periods of rainfall and sinking during periods of drought. Where there is no near-by valley into which the underground waters can drain they may accumulate in the ground until they stand almost at the surface. In some areas, even on crests, water can be had by digging 3 to 5 feet. In such areas it is apparent that, if the land is not absolutely flat, as it seldom is, some of the depressions will extend below the water level, in which case the ground water will enter the basin and form a marsh or lake. These conditions are exhibited in figure 1, which shows the relation of a pond and marsh to the water table, the normal level of which is indicated by N. The variation of the ground-water level already mentioned produces corresponding changes in the level of the water in the marshes and ponds. In very wet seasons, as when the water level is at W, the marsh may be converted into

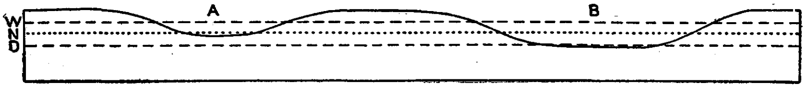


FIGURE 1.—Relation of marshes and lakes to water table. N, normal level of water table; W, level of water table in wet years; D, level of water table in dry years; A, marsh (in normal years) or lake (in wet years); B, lake (in normal or wet years) or marsh (in dry years).

a lake; whereas in dry seasons, when it has the position D, the marsh may become dry or the lake may be reduced to a swamp. Many such swamps dry up in summer, but too late to permit the planting of crops, and some are dry one year and wet the next; the uncertainty, however, is usually so great as to prevent their profitable cultivation.

Below the general ground-water level the earth is saturated with water down to the depth at which the pores become closed by the

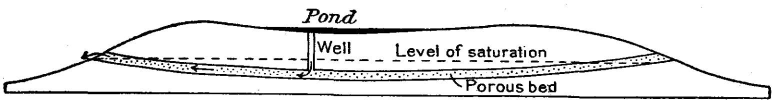


FIGURE 2.—Conditions illustrating the drainage of wells into a saturated stratum of lower head.

great pressures within the crust. Under such conditions there can be no nonsaturated layers, and drainage by wells will depend on the finding of a stratum in which the head of the water is less than that entering at the surface. Such conditions are found in basins of the form shown in figure 2.

Perched water tables.—Investigations have shown that a general ground-water level, such as is described in the previous section, seldom

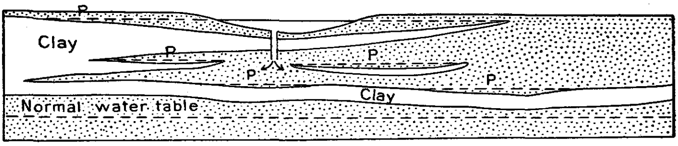


FIGURE 3.—Conditions encountered by wells sunk through perched water tables.

exists, its place being taken by local accumulations of ground water in a series of overlapping basins or strata, the surfaces of which, from their position above the ordinary water level, are known as perched water tables. Such conditions are illustrated in figure 3. One of the characteristics of perched water tables is that, except where all the underlying beds are composed of clay or other nonporous material, there is an unsaturated zone at some point below, into which it may be possible to drain surface waters through a well, as shown in the figure.

Impervious basins.—Even where the materials are pervious and unsaturated, there are times, as during heavy rainfall, when the water, instead of sinking immediately into the ground and joining the ground-water body, collects in rivulets on the surface and flows to depressions in which, if the bottoms are above the ground-water level, the water is gradually absorbed. In flowing over the surface, however, more or less fine silt, leaves, grass, straw, and like material is picked up and carried to the depression, where it is left behind as the water is evaporated or absorbed. In the course of time a coating of muck, consisting of the silt and other materials, is formed over the bottom, which may eventually make it so impervious that the water will be retained, as shown in figure 4. The conditions are closely similar to those of the perched water tables, except that the waters are entirely on the surface and are derived directly from rainfall rather than from the ground water. Unsaturated materials into which the water may possibly be drained are nearly always present.

Flood waters.—Floods as a cause of wet lands are, like lakes in impervious basins, independent of the position of the ground water, and, as a rule, flooded lands are the result of other than local conditions. Floods cover areas which are ordinarily drained, but which, owing to their low elevation and flatness, have become submerged by the overflow of streams whose channels, because of their gentle slope or crooked courses, can not remove the water as fast as it enters. The water generally returns to the stream on the falling of the flood, although the land may be so flat that the withdrawal is slow. In some places unsaturated gravels lie beneath the surface of the flooded land and it would be possible to reach them by drainage wells, although where the water stays over the land for a long time the deposits beneath it are likely to become saturated up to the surface.

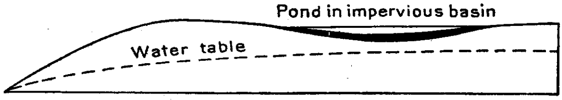


FIGURE 4.—Pond held in impervious basin above the water table.

Action of wells.—The efficiency of a drainage well depends on the difference in the head of the surface and the ground water, on the porosity or water-bearing capacity of the materials or deposits into which the water is to be carried, and on the grain of the materials. In order that the well may be effective it is necessary that the general level of the ground water must be lower than the depression to be drained, or else that the well shall strike an open passage or a deeper water-bearing stratum of low head. The material, if unsaturated, must be sufficiently porous and extensive to take up the water brought to it by the well. If saturated, the head of its waters must be less than that of the water of the basin to be drained, a condition which generally involves a low outlet, as shown in figure 2. The grain of the material must be so coarse that the water can readily enter it and drain away, or else there must be a definite open passage for its removal. If the water is not removed it will soon rise in the well until it reaches the level of the marsh or pond and drainage will come to a standstill.

EFFECTIVENESS OF WELLS SUNK IN DIFFERENT MATERIALS.

SURFACE DEPOSITS.

The surface deposits include unconsolidated materials, such as clay, sand, and gravel, and the heterogeneous mixture of all three deposited by glaciers and known as till.

Gravel.—Ordinary gravel consists of a mixture of pebbles of various sizes with a certain amount of sand that fills the spaces between the pebbles. If the pebbles are of uniform size and spherical shape, the absorptive capacity will range from a minimum of about 26 per cent to a maximum of 47 per cent. If the pebbles are flat the porosity is somewhat less, as it is if small pebbles and sand grains occupy the spaces between the larger pebbles. The average porosity of gravels is probably between 30 and 35 per cent. The grain of most gravels is so coarse that the water enters them readily without clogging the pores, thus availing itself of practically the entire porosity. Likewise if a gravel bed is cut by a ravine or valley its waters are quickly drained away. For these reasons gravel, where its structure and location are favorable, is an ideal material into which to drain wells.

Sand.—In sand the grains are generally more or less spherical and of relatively uniform size, from which it follows that the porosity will be high. Theoretically the porosity is greater than that of ordinary gravel, which consists of a mixture of large and small grains, but owing to the arrangement of the grains the actual porosity is very similar, averaging about 35 per cent. The grain of medium and coarse-grained sands is so coarse that water will enter them freely, provided it carries but little silt to clog the pores between the grains.

Clay.—Clays are silts composed of minute particles of rocks and minerals, which may contain hardly a trace of grit. Contrary to the common belief, tests show that they are exceedingly porous, many varieties having porosities as high as 45 or 50 per cent of their volume. Notwithstanding this high porosity, however, they can not be used for drainage, as their grain is so fine that water penetrates them very slowly and with great difficulty.

Till.—Till is a heterogeneous mixture of clay, sand, pebbles, and bowlders deposited by glaciers. In some till deposits bowlders and pebbles predominate and the mixture is almost or quite as porous as gravel; other deposits of till are prevailingly sandy; and in still others clay predominates and the till is almost as impervious to water as clay alone. As a whole, however, till is fairly porous and is capable of taking up considerable water, especially in its more sandy and gravelly portions, so that it affords a means of drainage by wells.

ROCKS.

In unconsolidated deposits such as those just described the spaces between the grains are unfilled. In most rocks, on the other hand, there are relatively few open spaces, even in rocks formed from sand, gravel, or clay. This compactness is due to the cementation of the rock by mineral matter deposited between the grains. Sands and gravels, which originally had porosities of 35 per cent, have only10 to 15 per cent after they have been consolidated into sandstone or conglomerate, and the porosity of slate is only about 5 as compared to 50 per cent in clay like that from which slate is formed. In the crystalline rocks the porosities are still smaller.

Conglomerate and sandstone.—As indicated above, sands and gravels retain porosities of 10 to 15 per cent after they have been consolidated into sandstone and conglomerates, and this makes them capable of taking up a considerable amount of water. The facility of entrance of the water, however, is greatly reduced by the consolidation, owing to the partial filling of the pores by cement, and it becomes necessary to guard carefully against clogging. Drainage into sandstones is said to have been successful in Michigan, and several wells in St. Paul and Minneapolis carry refuse into the porous St. Peter sandstone.

Slate and shale.—Both the small porosity of slate and shale, which, as stated, is only about 5 per cent, and their compactness of grain prohibit their use for drainage.

Limestone.—Limestone, like slate and shale, as a rule is of very low porosity, averaging about 5 per cent. The body of the rock is therefore of little or no use in drainage. Usually, however, limestones have more or less well-defined and open bedding planes and vertical breaks or joints along which water can move, as well as irregular tubular channels due to solution. Where not too far removed from valleys or depressions into which the water from the openings can flow, limestones may afford satisfactory drainage, for a well sunk into limestone is almost sure to encounter an open crevice of one type or another within a moderate distance of the surface. Wells sunk into limestone have been used for the disposal of sewage in Kentucky, Georgia, Florida, and possibly other States.

LOCATION OF DRAINAGE WELLS.

The best location for a drainage well is at the center of the marsh or pond to be drained, since the natural drainage is toward this point, but drilling in this place may be very inconvenient, owing to the presence of water. It may therefore be less troublesome to sink the well at some convenient point on the edge of the pond or marsh where the water can be kept out by a small earth dike while the inlet is being constructed. By this method the mouth of the well can be set as low as needed at the start and advantage taken of the extra head thus afforded. Ditches should be dug to this inlet and extended and deepened as the water is lowered until the entire area of the pond drains toward the well.

CONSTRUCTION OF DRAINAGE WELLS.

METHODS OF SINKING.

The methods of sinking wells differ greatly according to local practice and the nature of materials to be penetrated.

In rocks the standard churn drill and the diamond and calyx drills may be used, but the cost of the last two is prohibitive in drainage projects, and the churn drill, operated either from a derrick or a portable machine, is practically the only outfit used. In unconsolidated deposits also the churn drill may be used, but where no hard material is to be encountered the tube is more commonly driven. A hydraulic jet forced down an inner tube and rising between it and a larger outer tube is also used in sinking wells in loose deposits. Rigs in which the well is sunk by rotating a pipe fitted at the bottom with a saw-toothed steel shoe (usually in connection with a water jet) are also used, especially in the South. The cost is about the same with all methods, and all give about the same results, except that in the shoe method the water used to raise the drillings is used over and over again until it becomes a thick sludge which tends to clog the pores of the materials penetrated. Since in drainage wells it is very desirable that these should be kept open, the method is not to be recommended. Otherwise the rig which comes handiest may be used.

CHARACTER OF INLET.

Usually the top of the casing is left by the driller just as it was sunk, the condition when the water is admitted being as shown in figure 5. This is a very poor form of intake where the water enters rapidly, owing to the constriction of the water column, which, as shown in the figure, occupies only 50 to 75 per cent of the pipe. With a bell mouth, such as is shown in figure 6, nearly double the amount of water is taken in under ordinary conditions. This difference in the rate of taking the water is of great importance if time is considered, since a bell-mouth well, other things being equal, will drain a pond or swamp in about one-half the time required by the others. It has the disadvantage of being somewhat troublesome to construct where only the conveniences of a country blacksmith's shop are available, and it need not be used when no haste is necessary, for the regular casing will give the result desired. In figure 6 the diameter of the pipe is D; 0.62 times the diameter is the length at the end which is enlarged; 1.25 times the regular diameter is the diameter of the bell-mouth; and 1.62 times the diameter is the radius of curvature of the expanded end.

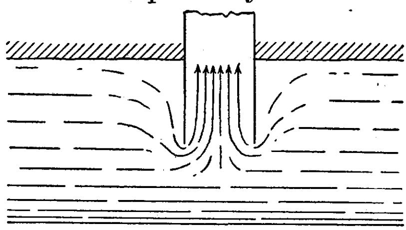


FIGURE 5.—Mode of entrance of water into ordinary casing.

PROTECTION OF INLET.

Many of the ponds and marshes to be drained contain floating vegetable matter—leaves, twigs, grass, water plants, and slime—which is rapidly drawn toward and into the well by the current set up by the indraft of water. As this material would soon clog the well it should be kept out by surrounding the well mouth with a brick or other curbing provided with screen-protected holes, as illustrated in figure 7, or by means of some other effective screen.

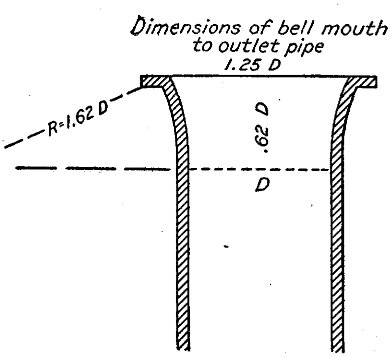


FIGURE 6.—Bell-mouth intake to drainage well.

CAPACITY OF DRAINAGE WELLS.

RELATION OF CAPACITY TO CHARACTER OF INTAKE.

The relation of the capacity of the well to the character of the intake has already been noted, it being pointed out that the capacity of a bell mouth, such as shown in figure 6, is nearly double that of a well having only the ordinary casing. The capacity of a well is also related to the character of its protection, screens of sufficient area and porosity to admit an adequate volume of water and at the same time keep out débris being essential.

RELATION TO EFFECTIVE HEAD.

In a well like that shown in figure 7 the theoretical head is the difference of level of the ground and the surface waters, or the distance from A to the water surface of the pond. If the material at the bottom is not very porous and the water enters slowly, the entire pipe will be filled, and the actual effective head, or that forcing the water

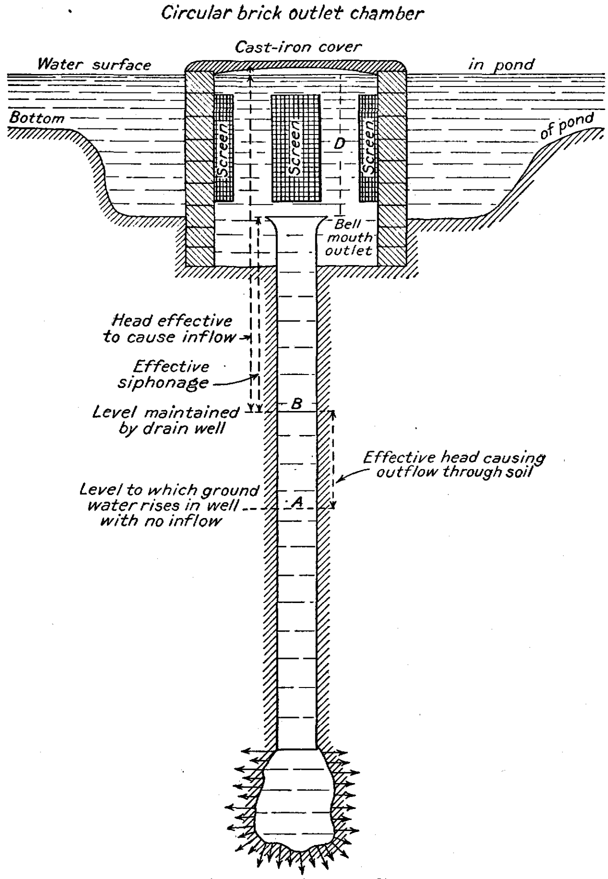


FIGURE 7.—Protection of intake of drainage well.

into the ground, will be the same as the theoretical head. If, however, the water is taken off rapidly into the ground, a sort of whirlpool will be formed, as a result of which the pipe is no longer completely filled, and the entire inflow may be only just sufficient to raise the water level from A to B. In this case the effective head forcing the water into the soil is the distance from A to B instead of from A to the surface as before.

RELATION TO SIPHONAGE.

In regard to siphon action in drainage wells R. E. Horton has made the following statement:[a]

In a well having a tight casing and a proper entrance the inflow will be augmented by siphonage or draft-tube action, the water being forced down by atmospheric pressure in a manner the inverse of the action of a lift pump. If there be free discharge at the bottom and if the well be over 33 feet deep, then the maximum possible draft-tube head of 32.8 feet may be available.

Unless the ground-water horizon is at exceptionally great depth, however, it will probably happen, as has been observed in practice, that the discharge head, *h*, required to take care of this large inflow of water, will cause the water level *B* to rise within much less than 32.8 feet of the surface, limiting the siphon head and dividing the total static head from *A* to the water surface of the pond in such a manner that the inflow head will just supply such a quantity of water as can be forced out of the bottom of the well by the remaining or discharge head. In any event the gain in capacity and rate of drainage which will result from siphonage will be very great; for example, with a pressure head *D* of 1 foot over the inlet, the discharge would be nearly doubled by the addition of 3 feet of effective siphonage and nearly trebled by the addition of 8 feet of effective siphonage.

AREAS DRAINED.

The area which can be drained depends on a great variety of factors. Under some conditions, such as those illustrated in figure 4, it is simply the visible water of the pond or marsh which must be considered, but under the conditions represented in figure 3, not only must the visible water be taken into account, but also the much more extensive area of tributary ground water. The pond can not be drained until the level of the ground water is reduced to a point below its bottom. It is therefore apparent that an extensive marsh can be readily and quickly drained if its bottom is above ground-water level, but that even a very small marsh that is continually replenished from the ground water can be drained only with great difficulty.

Again, the effectiveness of the drainage will depend to a considerable extent on the excess of head of the pond waters over those in the ground. If the difference is slight the drainage will necessarily be slow and difficult. The porosity of the bed into which the water is drained is also an important factor in determining the effectiveness, for unless the water is taken up and removed the well will be a complete failure.

[a] The drainage of ponds into drilled wells: Water-Supply Paper U. S. Geol. Survey No. 145, 1905, p. 35.

Some actual examples of the areas drained, as cited by R. E. Horton,[a] are presented below:

Areas drained in Michigan by wells.

Owner.	County.	Diameter of well.	Land drained.	Pond or marsh drained.
		Inches.	*Acres.*	*Acres.*
Fred Watkin	Jackson		35	2½
T. Eggleston	do	3		2½
C. I. Moe	do	3	10	
V. R. Horton	do	4	60	
W. H. Hartwell	Calhoun	4	40	

The time taken for drainage differs with the area drained and with differences in conditions. A pond covering 2 or 3 acres can be drained in a few months; if begun in March, the drainage will be completed in time for planting in May.

If the well enters an open cavity, as in limestone, the drainage is much more rapid and the area drained may be much larger than with other materials. In many drainage wells the capacity of the intake pipe is the only limiting factor.

COST OF WELLS.

The cost of wells varies according to the size and type of well, depth and length of casing, character of screens, if any, and other factors. Local practice also has much to do with the cost; a well at one point may cost twice as much as a well at another, even if the two wells are in adjoining counties. A drainage well of about the minimum practicable diameter—4 inches—will cost from 75 cents to $1.25 or more a foot, $1 being perhaps a fair average. In addition to this there will be a charge of about 25 cents a foot for casing. Screens for a 4-inch well cost from $4 to $8 a foot, according to material, method of construction, and size of mesh.

CAUSES OF FAILURE.

The causes of failure of drainage wells include what may be termed primary causes (or those dependent on the underground conditions, including the character of the materials and the hydrostatic conditions), and secondary causes, or those arising subsequent to the sinking of the well and independent of the underground conditions.

PRIMARY CAUSES.

Head of ground water.—Of the primary or original causes of failure the most common is probably the deficiency in head of the waters of the marsh. In many places the water in the drainage well stands so

[a] Loc. cit., pp. 30-39.

nearly at the level of that in the pond or marsh that little pressure is exerted by the ponded water and the inflow into the well is either feeble or lacking. In some wells the ground water is even under sufficient pressure to lift it above the level of the pond or marsh, and the well must be shut off to prevent further flooding of the depressions.

Absorptive capacity.—Next to the head of the underground waters, low absorptive capacity of the material encountered by the well is the most common cause of failure. Nearly all unconsolidated materials are porous, even clays having as high as 40 to 50 per cent of pore space, but many of them, owing to fineness of grain, so resist the entrance of water that they are unavailable for drainage. Another cause of failure arises from the pocket-like character of some of the sand or gravel layers, which are so small in extent that they quickly become filled to their full capacity, if they were not full at the start.

Rise of ground water.—Still another cause of decline and eventual failure lies in the lifting of the ground-water level as shown in figure 8. In this diagram A B represents the normal or original ground-water level. When the water is first turned into the well it is rapidly absorbed and the water table rises in the vicinity of the well. As the water continues to pour into the bed it becomes saturated to the

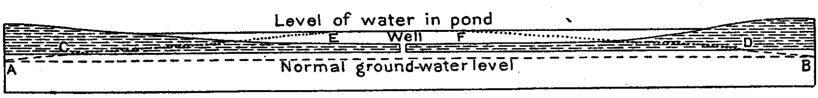


FIGURE 8.—Failure of drainage well due to rise of ground water. AC and BD, elevated water table due to influx of water from pond; CE and DF, line of head or theoretical extension of water table, touching pond level and preventing further inflow.

top and all further escape must be laterally toward A and B. At first the slope is fairly steep, but it gradually becomes more and more gradual, taking the form A C D B, the friction at the same time greatly increasing and acting as a restraint to the entrance of further water. If the friction becomes equal to or greater than the head, the inflow will stop.

SECONDARY CAUSES.

Obstruction of well mouth.—Most of the ponds or swamps to be drained contain much aquatic vegetation—reeds, grasses, etc.—which is torn up by ice or otherwise uprooted or broken and ever ready to accumulate at the well and to choke the pipe or clog the screens with which the well mouth is protected.

Clogging of receiving materials.—If coarse matter, such as leaves, grass, and weeds, are allowed to enter the well, the sand, gravel, or other material into which the water is drained will soon become clogged. The entrance of such matter is easily prevented, but the difficulty due to the clogging of the pores between the finer grains by silt is very serious in wells sunk in the finer materials.

Clogging of well screen.—The clogging of the screens is even more serious than the clogging of the sand itself, inasmuch as the screen, in order to keep it out of the well, must be of a mesh finer than the sand, and thus is still more likely to become clogged.

Entrance of quicksand.—If the wells are without screens quicksands may enter through the open bottom and gradually become compacted into a relatively impervious mass that fills the bottom of the well and greatly hinders the exit of the water.

Caving of the materials.—If the materials penetrated are fairly stiff, even if they are not consolidated, it is not uncommon to leave the well uncased. In such uncased wells, however, the material afterwards may become softened or loosened and cave in and clog the well, damaging or ruining it for purposes of drainage.

REMEDIES.

The procedure in case of failure will depend upon the probable cause of the difficulty as determined by a careful investigation of the conditions. If the stratum reached by the well is of low porosity or low absorptive capacity little can be done with it, and a lower bed should be tried. If the head is high enough to lift the underground water to the surface there is usually no remedy, as lower heads will rarely be found in underlying rocks. If the stoppage of drainage is due to the rise of the ground water or to the filling of pockets lower beds should be sought.

Of the secondary causes of failure the clogging of the well is the most common. The entrance of coarser floating matter can readily be prevented by proper screening, but the fine silts, which are hardly less objectionable, can not be so readily excluded. Much of this silt is washed in by the rains and settles in a few days or weeks, so if provision is made for closing the well until the water has cleared much difficulty will be avoided.

If the silt finds access to the well and clogs the pores of the sand one or another of several treatments may be adopted. Heavy pumping for a few hours may serve to draw back and remove some of the silt which has accumulated in the sand, leaving it free to take up water once more, or additional pressure may be brought to bear on the material at the bottom of the well by means of a water jet forced down by a steam pump, the object being to break up the film of silt which has collected on the surface of the material at the bottom of the well and to force it back and disperse it throughout the body of the deposit. For this purpose the "steam jet," used in drilling in Ohio, may be employed to advantage. By this apparatus highly heated steam forced into the material at the bottom of the well converts the water it contains into steam, causing an explosion that loosens the surrounding deposits.

USES OF DRAINAGE WELLS.

The foregoing discussion has dealt chiefly with wells sunk in unconsolidated materials, mainly to reclaim small ponds and marshes for cultivation. There are, however, several other important uses of drainage wells, some of which are considered in the following paragraphs.

MARSHES AND SWAMPS.

Marshes of drift regions.—Marshes have been drained in several northern States, especially Indiana, Michigan, Wisconsin, and Minnesota, the surfaces of which are in large part covered with deposits of gravel, sand, clay, and other unconsolidated material left by the glacier in the form of irregular hills and ridges, between which are numerous deep undrained depressions containing ponds or marshes. The conditions and results differ but little in the various States, the figures given for Michigan on page 16 being typical. Depressions on the higher lands can as a rule be successfully drained by wells, but many wells sunk in the deeper basins or on lower grounds strike flowing waters instead of waters of low head.

Coastal-plain swamps.—A special type of swamp is found on the upland crests between the streams of the Atlantic coastal plain in certain of the Southern States. These upland surfaces, which represent old sea bottoms, have been uplifted intact, retaining the same flat stretches and shallow depressions that marked them when originally deposited. Over these surfaces swamps, most of them characterized by heavy timber, have been formed. In general they are too extensive to be drained by wells, even if the head of the underground waters were not, as it frequently is, too high. Fortunately many of the streams in this region have cut deep valleys to which it is feasible to conduct the water by ditches.

River-bottom swamps.—River-bottom swamps are generally not like basins but are simply low tracts that border large rivers and are subject to overflow, the water standing on them temporarily rather than permanently. While the river is in flood there is of course no possibility of draining one of these swamps, for the water will come in from the river as fast as it is removed, and even after the river goes down much water is still held on the flat lands. The area of many of these river-bottom swamps is too extensive to permit their drainage as a whole. Some of them are underlain by beds of gravel or sand which are not completely saturated, and the surface water could be carried into these beds by wells, but except for small areas that could be separated from the surrounding wet lands by dikes, their drainage by wells would be impracticable and, in view of the cheapness of well-drained land in the same region, it is seldom desirable. Ditching is practicable in most of these swamps and in some of them is being pushed rapidly forward.

Sunk-land swamps.—In southeastern Missouri, northeastern Arkansas, and western Tennessee there are numerous depressions due to local sinking of the land caused by the New Madrid and other earthquakes. The largest of these is Reelfoot Lake, in northwestern Tennessee. This lake is 20 miles long and 5 miles broad, and covers land which, if reclaimed, would afford agricultural soils of the finest quality. The drainage of this lake is now under consideration, but the work must be done entirely by ditching, the water table being too high for drainage by wells.

Extensive sunk-land marshes also occur along Varney and other rivers in Missouri and St. Francis River in Arkansas, and many small basins or sloughs lie in the woods in northeastern Arkansas. Marshes near a river are controlled by river level, and the drainage of most of them is impracticable. A smaller slough can be drained by wells when the region in which it lies is occupied by settlers.

PONDS.

The drainage of ponds in Michigan by wells has already been noted (p. 16). In Minnesota very similar results have been obtained at several places, and in Wisconsin, Indiana, and other States where the surface deposits are of a similar type drainage wells have been successfully employed. In these States most of the wells drain into beds of sand and gravel in the drift, although a few of them in Michigan are said to drain into sandstone, and some at Minneapolis and St. Paul discharge refuse into the St. Peter sandstone. In Georgia and Florida the receiving bed of a number of wells is limestone. By a drainage well sunk at Quitman, Ga., 1,500,000 gallons were drained from a pond in a few hours. In Virginia, Kentucky, Tennessee, Indiana, and other States in which limestone occurs it is a common practice, it is said, to dig or drill for the purpose of carrying the water out of sinks into the underlying limestone.

CELLARS.

Cellars have been drained by wells at Minneapolis, St. Paul, Hampton, Blooming Prairie, Bricelyn, and Geneva, and doubtless at other places in Minnesota, as well as in other States where the surface is underlain by porous beds of sand or gravel or by limestone with open crevices.

INDUSTRIAL WASTES.

Little is said by owners of borings into which industrial wastes are being turned, but it is probable that such drainage is practiced in Minneapolis and St. Paul and in certain limestone areas in Georgia and Florida. Creamery waste products are disposed of in this way in some country towns.

SEWAGE.

In Kentucky, Georgia, Florida, and other States sewage is at many places poured into borings in limestone. Among the cities in which there are public or private sewage wells are Georgetown, Ky., and Orlando, Ocala, Live Oak, Gainesville, and Lake City, Fla.

POLLUTION OF GROUND WATER BY DRAINAGE WELLS.

NATURE OF POLLUTION BY WATER TAKEN FROM DIFFERENT SOURCES.

Drainage wells have been successfully used in many places and may be multiplied to advantage, but they are likely to pollute the ground water.

Ponds.—The water of ordinary small ponds on a farm is not of good quality. Usually shallow, the water becomes much heated and contains vegetable growth, which gives it a decided taste and color. Cattle may drink from the pond or stand in its waters, polluting it in various ways. A drainage well adds the organic matter and pollution to the ground water, materially lowering its quality.

Marshes.—What has been said of ponds applies also to marshes. Swamps contain even more organic matter than ponds, and consequently their drainage into the ground water is a source of greater pollution from vegetable though not from animal refuse.

Fields.—Waters derived from fields are generally somewhat polluted. In running down slopes they carry along decaying vegetable matter; in cultivated fields where manure or other fertilizer is used and on land where cattle are pastured they gather much more objectionable pollution and carry it to the ground water through drainage wells.

Cellars.—Water in cellars has fallen as rain in the yard or vicinity and seeped down through the soil into the cellar, perhaps made foul by privy wastes, slops, or other pollution. It is needless to say that such water does not constitute a desirable addition to the ground-water supply when it is conducted into the ground through a drainage well.

Wastes.—Most industrial wastes are obnoxious in taste and odor, and some of them are deleterious to health, but generally not so dangerous as water taken from the farm and barnyard. Nevertheless, if they are carried into the ground water by a drainage well, they will unfit it for domestic uses.

Sewage.—The drainage of sewage into the ground water may spread disease to all who drink the water.

EXTENT OF THE POLLUTION.

The distance to which contaminating material will pollute ground water will differ greatly under different conditions. If the polluted water is added to saturated sands or gravels, its effect will not extend to a great distance, usually not more than a few hundred feet, owing to the slowness of movement of the water. If added to an open sand, the polluted water may spread to a considerable distance. In general, however, in such material the area affected is not likely to be much if any greater than the area drained. The extent of the pollution also depends on the amount of water introduced, the water from a pond or marsh spreading much farther than that from a cellar or cesspool. It is fortunate that the most dangerous sewage introduced into sand or gravel spreads but little as compared with the relatively harmless water from ponds.

If a drainage well enters limestone, the conditions are wholly different. The polluted water or sewage enters an open passage in which it may be conducted for a long distance without dilution or purification. A public well that encounters such a passage may communicate typhoid fever to hundreds of persons, even if the well is miles from the source of contamination.

RECOMMENDATIONS.

1. The emptying of sewage into drainage wells is very dangerous and should be avoided.
2. The drainage of industrial wastes into borings is objectionable if not dangerous, and the practice is to be condemned.
3. The drainage of cellars into wells is objectionable in towns where near-by wells must draw on the ground water into which the cellar waters are carried. In the country the practice is not objectionable if the water is carried through a tight casing to a bed lower than that which supplies the local water wells or to a higher bed if the water wells are tightly cased through this bed and through a thickness of impervious material sufficient to prevent any possibility of contamination.
4. The drainage of most ponds and swamps into wells is unobjectionable, for they are far from houses and from wells that supply drinking water. The movement of ground water is normally away from rather than toward the houses, the addition from the pond serving, at the worst, to back up rather than to reverse the movement. Moreover, water does not spread far underground. On the whole the drilling of wells for draining swamps and ponds should be encouraged, but the usefulness of the wells is limited to ponds covering a few acres and to basins not exceeding in extent 75 acres.

THE FREEZING OF WELLS AND RELATED PHENOMENA.

By Myron L. Fuller.

CONDITIONS OF FREEZING.

Region affected.—Throughout many of the Northern States much trouble is caused by the freezing of wells, not so much with the shallow dug wells as with the deeper drilled ones. Many wells in the North can be kept in use during the winter only with the greatest difficulty, so that the determination of the cause of the freezing and of means for its prevention is of great practical importance.

Open wells.—In open wells, including in this class the dug wells not provided with covers, the cold air—often many degrees below zero—is free to enter and displace the air of the wells, which, owing to its contact with the water and the unfrozen earth, is generally considerably warmer. Under such conditions, although the temperature of the entering air is somewhat modified by mixture with that already in the well and by contact with the walls, freezing often occurs at considerable depths, and the well is rendered useless during the continuance of cold weather.

Covered dug wells.—In dug wells protected by covers there is generally little trouble from the freezing of the water unless it happens to stand very near the surface. Although few well coverings are tight enough to exclude the cold air, it penetrates so slowly that the temperature in the well, owing to the warmth given off by the earth and the ground water, seldom reaches the freezing point. In some wells, however, where open, water-free gravels occur above water level, much trouble is experienced.

Driven wells.—In the simpler type of driven wells, consisting of a single continuous casing, or of double tubes, both of which are carried below the ground-water level, little or no trouble is caused by the freezing of the water in the well, except, perhaps, when its level is very near the surface. The amount of cold air entering through the pump is insignificant, and there is no material circulation of air in the surrounding materials, and therefore no adequate cause for freezing.

Drilled wells.—Most of the wells subject to freezing are drilled or double-tube driven wells in which the inner or pump tube is carried below the outer casing, stopping in some porous stratum (figs. 10 and 11), or wells drilled in limestone or other rocks that contain open solution passages (fig. 12). The cause of freezing in these wells is discussed on pages 29 and 30.

Pumps.—Pumps are certain to freeze if the cylinders are near the surface, as the water left in the valves and box after pumping freezes before it can drain back into the well. Where the cylinder is placed at a considerable depth, however, this difficulty is avoided, except in what are known as the drilled wells, just noted. It is therefore the nearly universal practice to set the cylinder at as great a depth as possible and where practicable to surround it with tightly packed earth to shut out the air.

Character of material penetrated.—An investigation by F. G. Clapp of the wells of Maine, a large part of which are in granites, slates, shales, and other hard rocks that are free from openings, showed no instances of deep freezing. In Minnesota, North Dakota, and Nebraska, on the other hand, large numbers of wells that penetrate porous deposits or cavernous limestones freeze every winter. In Wisconsin and Michigan freezing, though less common, occasionally occurs, especially in some of the wells in the porous gravelly hills and ridges. Even in Pennsylvania freezing, apparently due to the same causes, occurs in oil wells at depths of thousands of feet. In States farther south, especially in Iowa, Missouri, Kentucky, and Indiana, wells occasionally freeze, both those in the porous surface deposits and those in limestones.

ATTENDANT OR RELATED PHENOMENA.

The phenomena attendant on the freezing, apparently due to the same or similar causes, include the indraft and outdraft of air that produces sucking and blowing wells, changes in the character of the water, fluctuation of the water level, and changes in the discharge of flowing wells. Each of these is not only of great interest to the owner of the well or to the driller, but presents an economic problem of practical importance.

Blowing wells.—Wells that emit currents of air from their mouths are called blowing wells. Blowing is not confined to drilled wells, but is noted in many dug wells, the air escaping through cracks or other openings in the covers. It was reported to the writer that the current passing out through the knot hole in the cover of one well was strong enough to lift a hat several feet into the air. At some times the whistling of the escaping air through the planks or pipes can be heard for several rods; at other times the current is strong enough to operate small whistles whose sound is loud enough to be heard for a mile or more in still weather. In some wells a dull roaring sound is heard as the air rushes through the casing; in other wells the air can be heard bubbling through the water.

Breathing wells.—In most blowing wells the blowing is not continuous but alternates with sucking; such wells are more properly known as breathing wells. Probably most of the "barometer" or "weather" wells are of this class, although the indraft is usually less rapid and less conspicuous than the outdraft, and in warm climates, where freezing never occurs, may be overlooked. Its presence is, however, abundantly demonstrated. (See p. 26.) Even if no indraft is observed, it is noted that the blowing is weak or ceases at times, so that there is a rhythm in the movement of the air. In humid regions the blowing is, as a rule, most marked before rain storms, and the sucking or indraft of air occurs in clearing weather after a storm. In other words, the blowing occurs during periods of low barometer and the indraft occurs in periods of high barometer. The blowing may be associated with some particular direction of the wind, as would be expected from the fact that the direction of the wind in rain storms is different from that prevailing in clear weather. Some wells show fluctuations with very small changes of barometric pressure, even with the diurnal changes, blowing at times of low pressure, as at 3 a. m. and 4 p. m., and sucking at times of high pressure at 10 a. m. and at 9 p. m. In some wells there is a noticeable "lag" in the phenomena, the blowing and sucking continuing an hour or more after the limits indicated.

Sucking wells.—Wells that suck in air at times are common, but those with continuous indrafts are very rare. Two such "sucking" wells have, however, been reported in Tertiary limestone near Boston, in southern Georgia. Where indraft alternates with outdraft the movement has a direct relation to barometric changes, but where the indraft is continuous no such relation is observed, the phenomena apparently being independent of barometric pressure. In the wells noted above the air is sucked in by streams of water running in caverns in the rock.

Fluctuation of water level.—In many parts of the country the water level in certain wells rises and falls with changes of weather, being highest in periods of low barometer and lowest when the barometer is high. In some wells the difference amounts to several inches, and a well that must be pumped in clear weather may flow during storms or when the wind blows from a certain direction.

Variation in discharge.—Some flowing wells discharge only during periods of low barometer. Others flow with greatly increased volume at such times, the effect being especially marked in wells of large diameter that flow when they are only a little below their highest level or maximum head. In such wells the discharge may be increased several hundred per cent during periods of low pressure.

Changes in character of water.—Most drilled wells yield perfectly clear water after they have been in use a short time, but although the water is ordinarily clear, it becomes cloudy or milky on the approach of storms and occasionally it becomes bright yellow or deep red during periods of low barometer. Examination of the water shows that its milkiness is caused by a small amount of suspended silt or clay and the yellow and red colors by suspended fine particles of iron oxide (yellow and red ocher). The presence of iron oxide makes the water unfit for use.

DISTRIBUTION OF PHENOMENA.

The phenomena described are of widespread occurrence. Blowing wells are especially common. The following list is based in part on data furnished by Samuel Sanford, of the Bureau of Mines.

Localities at which well phenomena have been noted.

Blowing and breathing.

States.	Number of localities.	Depth.	Material.	Age of material.
		Feet.		
Arizona	One			
Arkansas	Several	[a] 100	Limestone	Paleozoic.
Indiana	One	120	Sandstone	Do.
Iowa	do	70	Gravel	Pleistocene.
Louisiana	do	80	Sand	Tertiary.
Michigan	do		do	Pleistocene.
Minnesota	Many	50-150	Sand and limestone	Pleistocene and Paleozoic.
Missouri	do	[a] 170	Limestone	Paleozoic.
Nebraska	do	[a] 1,000	Sandstone, gravel, and sand.	Cretaceous, Tertiary, and Pleistocene.
New York	Several	[a] 150	Gravel and sand	Pleistocene.
Oregon	One	[a] 360	Sand and sandstone	Tertiary.
South Carolina	do	120	Sand	Cretaceous.
Texas	Several	[a] 300		
Washington	do	[a] 500	Lava beds	Tertiary and Pleistocene.
Wisconsin	One	[a] 100	Sand	Pleistocene.

Continuous indraft.

Georgia	Two	100-150	Limestone	Tertiary.

Variations of head and flow.

Michigan	Many	25-200	Drift	Pleistocene.
Minnesota	do	35-150	do	Do.
Wisconsin	Several	56-150	do	Do.

Change in character of water.

Minnesota	Several	37	Drift	Pleistocene.

[a] Depth of deepest well here listed for the State.

CAUSES OF FREEZING AND ATTENDANT PHENOMENA.

GENERAL CAUSE.

A study of the phenomena as a whole shows that they are only casually related to changes of temperature or of wind direction, but that they agree very intimately with barometric changes, the relation of the blowing to storms being recognized by nearly every owner of a blowing well. On the one hand, freezing, indraft of breathing wells, low water level, small discharge and clear water all occur in clear weather during periods of high barometer; on the other hand, the thawing of the well, the melting of the surrounding snow, blowing, high head, strong discharge, and milky or discolored water occur during periods of low barometer. This association, which is constant, together with the fact that the results are exactly what would be expected from barometric fluctuation, leaves little room for doubt that this is the general cause of the phenomena.

CAUSE OF FREEZING.

The freezing of wells seems to be due to the indraft of cold air at periods of high barometer, the air passing down the well (see p. 29) and freezing the water. When, on a change of weather, the direction of the air current is reversed the well thaws and the snow about the well mouth melts.

CAUSE OF FLUCTUATIONS IN WATER LEVEL OR FLOOR.

The water in many deep wells is under more or less hydrostatic pressure, which is opposed by the pressure of the air, the level at which the water stands representing the result or the balance of the two forces. If the pressure of the air is lessened and the hydrostatic pressure remains the same the water level in the well will rise, and if the atmospheric pressure increases the water level will fall. In some nonflowing wells the increased head will cause the water to flow; in flowing wells it increases the volume of discharge.

CAUSE OF CHANGE IN CHARACTER OF WATER.

As low air pressure causes increased discharge in certain flowing wells, and as increased discharge produces increased velocity of the water both in the well and in the material from which the water is derived, it often happens, where this material includes more or less silt which is too coarse to be affected by ordinary currents, that quantities of silt are loosened under the increased velocity and taken up by the water, producing milkiness. Iron oxide may be precipitated in the earth from chalybeate waters, although it may not ordinarily be present in amounts large enough to be noticeable in the water drawn from a well, but during periods of low barometer this oxide is disturbed in much the same way as is the silt, and mixes with the water as a yellow or red precipitate, rendering it unfit for use.

In wells that do not flow occasional turbidity is more difficult to explain, but the motion of the ground water tapped by these wells is no doubt affected by an increase of discharge at places of constant outlet—an increase caused by change in barometric pressure—and as the phenomena occur under identically the same conditions it is

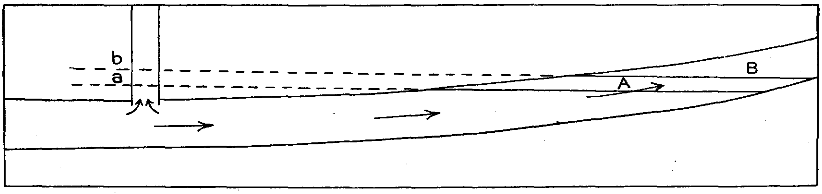


FIGURE 9.—Supposed conditions producing discoloration of waters in nonflowing wells. A, Normal water level in bed; a, normal water level in well; B, level in water bed during low barometer; b, level in well during low barometer.

probable that they are due to the same general cause. The disturbance in the well is probably not caused by the slight rise of the water in the well (a to b, fig. 9), but rather by a general movement of the whole water body (A to B), due to relief of pressure on the water surface, the silts or precipitates throughout the whole mass being disturbed. In this connection it may be said that most of the wells exhibiting this phenomena are shallow, so that direct barometric action on the water is possible.

REMEDIES.

SIMPLE TREATMENT.

Several simple methods of preventing wells from freezing are in common use, but owing to a failure to understand fully the causes of the freezing many of these methods fail and others are only partly successful. Some persons have the idea that freezing is caused by the chilling of the air inside the well by the transmission of the cold outside air through the casing, to remedy which the pumps are carefully wrapped in cloth, packed with straw, or otherwise protected. As a rule, this protection is entirely without effect, for the freezing does not occur in the manner assumed, but by access of air to the pipe at considerable depths. Other persons partly recognize the true cause of freezing and make an attempt to prevent access of air by packing earth, straw, or other material about the well. This practice is partly successful, as it tends to check the indraft of air, but the materials used are as a rule so porous that more or less air gets through them and the well freezes. The use of manure is somewhat more effective, for it warms the air that passes through it, but it involves great danger of pollution.

EFFECTIVE TREATMENT.

Freezing is due to faults in the construction of the well itself and can ordinarily be prevented only by remedying the defects of construction.

Open wells.—The air obtains access to open wells through the soil at the junction of curb and cover and through cracks in the curb or in the cover. As the soil is usually frozen in winter, little air enters the well in this way. The junction of curb and cover is tight in but few wells, and the cover itself, if of wood, is tight in none. The remedy for freezing consists in substituting cement for wood and in tightly fitting it to the curb, which should also be coated with cement for some distance below the surface.

Cased wells with escape at bottom.—The conditions in a cased well with escape at bottom are represented in figure 10, in which A is the outer casing; B, the inner or pump tube; C, the pump cylinder; and D, the well point. When the barometer is high the air is sucked in at E, at the mouth of the well, and passes off into the unsaturated sand at F. If the well is not pumped, it will not freeze at first, as the pipe contains no water above the water level G. If the well is pumped and the water is raised to the cylinder C and up pipe B, the cold air passing between A and B is likely to freeze the well. Even if the well is not pumped, the air current, if long continued, will eventually freeze the ground water at G and possibly also the water in the pipe.

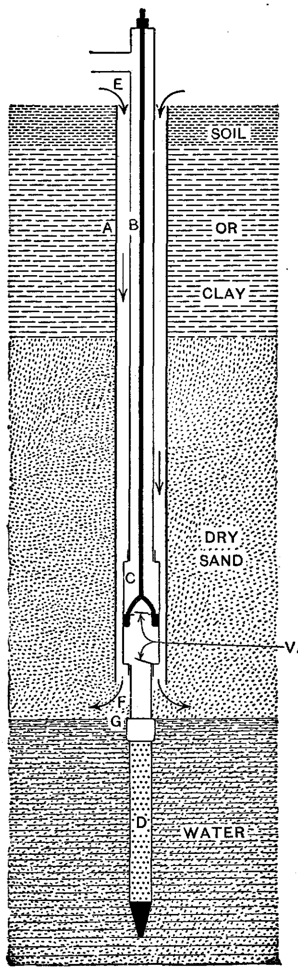


FIGURE 10.—Conditions governing freezing in cased well with escape of air at bottom. (Sanford.)

The remedy for freezing in such a well is to fill tightly the space between A and B at a point near the surface with some impervious material. A filling of cement resting on an improvised plug will probably effectively prevent freezing. The homemade rag packing sometimes used is generally too porous, permitting enough air to get through to produce freezing. Rubber plugs are effective, but care should be taken not to use materials which can damage the water if they happen to drop to the bottom of the well. Manure should never be used about a well cased in the manner shown in the figure, as it can get to the water just as well as the air can.

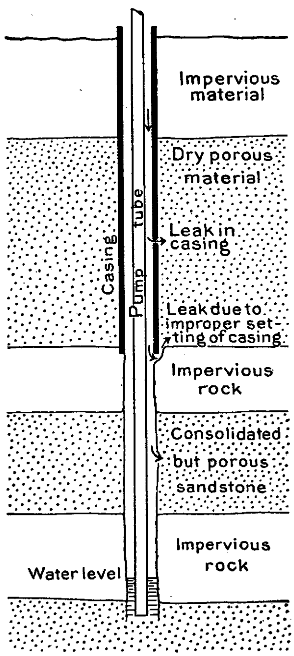


FIGURE 11.—Conditions governing freezing in wells with leaky casings and porous walls.

Wells with leaky casings.—Figure 11 shows a well which, though cased to a certain depth, has developed leaks by corrosion or imperfect joints and by careless setting of the casing in the rock. During periods of high barometer cold air enters the mouth of the well, passes downward between the casing and pump tube, and out into the porous stratum. The constant indraft of cold air quickly freezes the water remaining in the pipe after pumping.

The proper treatment is to plug effectually the space between the two pipes at a point near the surface.

Wells in porous rock.—The conditions in a well passing through porous rock are also illustrated in figure 11, in which the bed of sandstone, although stiff enough to stand without casing, may be sufficiently porous to permit large amounts of chilled air to enter from the well during periods of high barometer, resulting in freezing, as before. The remedy is a tight packing between the two pipes at a point near the surface.

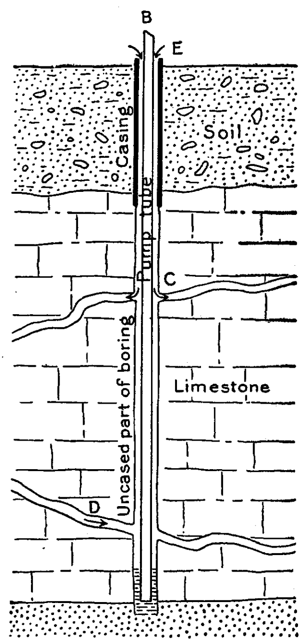


FIGURE 12.—Conditions governing the pumping in limestone wells.

Wells encountering open passages.—Wells encountering open passages are practically limited to limestone in which solution channels have been formed by circulating waters and later abandoned. In figure 12, which shows such a well, B is the pump tube and C an open passage into which air entering at the mouth of the well during periods of high pressure is carried off into the rock, producing a circulation which soon freezes water standing in the inner pipe. The treatment is the same as that required for the well just described; it consists of plugging the well at E.

In many wells, however, this treatment is ineffectual, indicating that the cold air is not entering at E, but is circulating through underground passages, as indicated by the arrow at D. In such wells it becomes necessary to set the plug at the point where the passage is encountered, in this case at D. In some wells, as in one near Wabasha, Minn., the crevices through which the air is circulating are so numerous that the space between the outer and inner tubes must be filled from bottom to top with cement.

OCCURRENCE AND COMPOSITION OF WELL WATERS IN THE SLATES OF MAINE.

By Frederick G. Clapp.

INTRODUCTION.

There is a popular belief that little water can be found in slate. This idea is based on the very fine grain and impervious nature of the rock and on the fact that in regions where the strata are nearly horizontal slate acts as a confining stratum to hold water in more porous beds. Investigations of the underground waters of Maine in 1906 have shown, however, that in that State the slates contain more water than any other kind of rock, and that where they do not contain lime in detrimental quantities their water is the best found in the State.

CHARACTER OF MAINE SLATES.

The slates found in southern Maine are exceedingly diverse in character. Most commonly they are typical fine-grained, hard, black rocks, consisting of hardened clay, but in places they are schistose and even grade into true schist. In northeastern Maine and at a few places elsewhere in the State they are calcareous. Practically all the slates in the State are highly folded, and the stratification and cleavage planes dip at high angles. Near the coast the strike is diverse, but in many parts of central Maine it is very constant, being about N. 60° E. over broad areas. The dip is not so uniform, but is nearly everywhere high. The slates range from very hard to very soft.

WELLS IN SLATE.

NUMBER.

In the investigations all records of wells in Maine more than 50 feet deep were compiled, so far as they could be obtained. Nearly 600 such wells were found south of the forty-fifth parallel of latitude. For 385 of these it was possible to determine with certainty the type of rock penetrated. Of this number 214 were in slate and 37 in schist. As schist is in most places a metamorphic form of slate it is considered here with the slate. Thus, in southern Maine, 251 wells, or 70 per cent of those of which the type of rock is known, are in slate or schist. In northern Maine practically all the drilled wells are in slate or similar rocks; many of the rocks in this region are spoken of as "slated limestones," but they are in reality moderately calcareous slates.

PROPORTION OF SUCCESSFUL WELLS.

The following table includes all Maine wells more than 50 feet in depth in which the character of the rock could be determined:

Proportion of successful wells in various rocks in Maine.

Type of rock.	Successful wells.	Unsuccessful wells.	Total.	Percentage successful.
Schist	34	3	37	92
Slate	191	[a] 23	214	88
Complex	42	[b] 6	48	87
Granite	51	8	59	86
Gneiss	12	2	14	86
Trap and greenstone	10	3	13	77
	340	45	385	88

[a] Includes six wells ruined by entrance of ocean water.
[b] Includes one well ruined by entrance of ocean water.

From the table it will be seen that the proportion of successful wells (wells from which enough water for the domestic use of a moderate-sized family can be obtained) ranges in various rocks from 92 to 77 per cent. The table does not include gravel wells, which nearly always get a supply, but in which the character of water is uncertain. The table shows that in slate and schist the chances of obtaining water are somewhat greater than they are in any other type of solid rock in Maine. There is, however, a surprising uniformity in the proportion of successful wells in various rocks. It is also surprising to note that schist appears to offer better chances than slate, having 92 per cent of successful wells, whereas slate has only 88 per cent. With the 23 unsuccessful wells in slate, however, are included six wells which were ruined by the entrance of salt water, for the reason that they were drilled within a few feet of the ocean. These wells would undoubtedly have been successful if drilled a few hundred feet inland, and if the figures in the table should be changed so as to include these six wells with the successful ones, the percentage of successful wells in slate would be brought up to 91, corresponding closely with the proportion of successful wells in schist, with which no salt-water wells were included.

The table does not include any wells north of the forty-fifth parallel of latitude, as that region was not included in the investigation.

It is believed, however, from a hasty reconnaissance of the conditions in northern Maine, that practically all wells drilled in slate in that region are moderately successful.

WATER SUPPLY AND DEPTH.

In most rocks there is a more or less definite relation between the success of a well and its depth. In granite, for instance, there is a marked decrease in the amount of water found below about 200 feet. In order to learn whether any similar relation exists in slate the following table was compiled, taking into account all drilled wells more than 50 feet deep in which the rock is known definitely to be slate.

Data of slate wells in Maine.

Depth (feet).	Number yielding, in gallons per minute—					Successful; yield not known.	Too little water (failures).	Water not usable.	Total wells.	Per cent successful.
	1 to 5.	6 to 10.	11 to 50.	50 to 100.	Over 100.					
50-100	30	7	11	1	....	63	5	6	123	91
100-200	9	3	14	....	....	15	7	2	58	85
200-300	3	3	9	2	1	12	1	1	32	94
300-400	1	1	....	2	....	....	....	1	5	80
400-500	....	....	2	....	....	....	....	....	2	100
More than 500	....	....	1	....	....	....	1	....	2	50
	43	14	37	5	1	90	14	10	214	88

The most important column in this table is the last, which shows the percentage of successful wells of various depths. The unsuccessful wells include both those in which too little water was obtained for the use of a family of ordinary size, and those in which the water was so poor as not to be usable. Of the ten poor wells, six were ruined by the incursion of salt water.

The proportion of successful wells in granite and other crystalline rocks decreases from about 95 per cent for wells less than 100 feet deep to a low figure for the deeper wells. In slate, however, there is no such regular decrease with increase in depth. Of the 123 wells between 50 and 100 feet deep 91 per cent were found to be successful; of the 58 wells between 100 and 200 feet deep 85 per cent were successful; and of the 32 wells between 200 and 300 feet deep 94 per cent were successful. The wells deeper than 300 feet are few and the figures for them carry little weight. Evidently, however, there is no close relation between success and depth of well. The greatest success was obtained with wells between 200 and 300 feet deep.

The facts above stated were unexpected by the investigator, for it had been supposed that, as in granite and crystalline rocks in this and other States, little water would be found in slate below 200 feet. The difference is probably due to the difference in the character of the rock. In granite and most crystalline rocks the water occurs entirely in joint cracks, which tend to close with increase in depth and are few in number below 200 feet, but in slate the water occurs not only in the joint cracks but also in minute crevices along the stratification and cleavage planes, and in calcareous slates it may occur in cavities formed by solution. The stratification and cleavage planes, like the joint cracks, probably close with increasing depth, but as they do not correspond in direction with the joint cracks the pressure of the rock in any particular direction would close only a part of the cavities which might hold water. It can not be said definitely what proportion of the Maine slates are calcareous enough to contain dissolved cavities, but it is known that in some places thin layers of limestone are interstratified with the slate, and it is probable that in such places the water occurs in cavities.

The chief lesson to be learned from the above table is that in drilling in the Maine slates the chances of obtaining a sufficient and suitable water supply at less than 200 feet from the surface are about 90 in a hundred. If such a supply is not found, however, it is worth while to continue the drilling to at least 300 feet. If the yield is still insufficient, it might even pay to drill 100 or 200 feet deeper. In all rocks, however, great pressure exists below the surface, and it is probable that the crevices are closed below the depth of a few hundred feet. The statements made here do not apply to any kind of rock except the slate of compact type and possibly to schist.

PRINCIPAL WATER VEIN.

The foregoing statements as to depth of well do not mean that the principal vein of water in the wells is always found at the maximum depth. In only 123 out of the 214 wells drilled in slate could the depth to the principal water vein be ascertained. The relation of the depth of this vein to the depth of the well, so far as known, is given in the following table:

Relation of principal water vein to depth of well.

Depth of well (feet).	Number of wells in which depth to principal water vein (in feet) was—						
	0-50.	50-100.	100-200.	200-300.	300-400.	400+.	Total.
50-100	27	45					72
100-200	3	8	12				23
200-300	3	3	7	8			21
300-400	1	1		1	1		4
More than 400					1	2	3
	34	57	19	9	2	2	123

The most interesting feature brought out by the foregoing table is that the depth of the principal water supply generally bears little relation to the depth of the well. Usually in slate wells there is no one crack which yields all the water, but many cracks which furnish water, so that with continued drilling the supply becomes sufficient. In most wells one opening yields more water than the others, and this is called the "principal water vain." A comparison of the figures shows that in slate the supply is not necessarily to be expected within 50 feet of the surface, although it is frequently found at shallow depths. The figures corroborate those in the first table, showing that wells may be drilled to 200 feet, or even to more than 300 feet, with a fair expectation of increased yield.

FLOWING WELLS.

In general, flowing wells are not looked for in slate. In Maine, however, there are 24 flowing wells in slate, out of 39 recorded in all kinds of rock. Ten of the flowing slate wells are in Cumberland County, 5 are in Piscataquis County, and the remainder are scattering. The best flowing wells in the State are those at Greenville, in Piscataquis County, where the water rises 10 to 20 feet above the surface. All the flowing wells are believed to be due to the arrangement of joint cracks in the rock by which the water penetrates downward beneath an impervious surface coating of bowlder clay and reaches the surface when tapped by wells at suitable points in the valleys.

COMPOSITION OF SLATE WATERS.

It is not supposed that the quality of slate waters of Maine is characteristic of all waters occurring in slate in other regions. There is, however, a considerable degree of probability that the average quality of water found in this rock in Maine is fairly typical of the quality of that from the metamorphic slates which are so widely distributed throughout the country.

In the investigation of the underground waters of Maine over 100 analyses of slate waters were collected and compiled. Of these about 25 were detailed chemical analyses made by Prof. F. C. Robinson, of Brunswick, Me. These record the character of the water with considerable accuracy and are probably the most reliable analyses of slate waters known. In order to give a good idea of the character of these waters, the following table is appended, giving 13 characteristic analyses of waters widely scattered throughout the State:

Composition of waters from wells drilled in slate in Maine.

[F. C. Robinson, analyst. Quantities in parts per million.]

No.	County.	Locality.	Owner.	Depth (feet).	Total solids.	Organic and volatile matter.	Silica (SiO_2).	Iron and aluminum oxides (Fe_2O_3+Al_2O_3).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Sulphate radicle (SO_4).	Chlorine (Cl).
1	York	Kittery	Roland Thaxter	75	208.7	14.6	11.0	3.2	46.8	12.8	26.6	8.7	14.1	40.[illegible]
2	Cumberland	Cape Cottage	Amos Miller	115	140.0	22.5	9.0	.9	43.0	2.4	10.8	3.8	15.1	18.5
3	....do	Mere Point	W. D. Pennell	67	88.2	29.9	8.8	2.0	7.0	4.5	7.3	1.5	22.4	10.4
4	Kennebec	Winthrop	C. M. Bailey Sons & Co	307½	226.9	20.3	15.5	2.0	56.7	6.3	26.6	5.0	62.9	7.5
5	Waldo	Belmont	Horace Chenery	187	138.2	9.5	16.8	2.5	23.1	6.4	15.2	6.1	13.6	5.0
6	....do	Searsport	W. E. Grinnell	100	162.4	10.6	21.0	3.0	28.4	5.1	21.2	6.2	27.5	22.0
7	Hancock	Bucksport	Eastern Maine Conference Seminary	308	115.7	9.6	15.1	1.8	25.5	3.6	17.7	2.2	22.3	6.5
8	....do	Hancock	Jeremiah Stratton	65	108.8	10.5	14.8	1.0	14.7	2.9	6.7	2.3	10.9	11.9
9	Penobscot	Bangor	Maine Creamery Co	120	86.0	21.4	6.7	.7	20.1	5.7	4.0	.8	5.9	21.0
10	....do	....do	High School	217	180.0	37.1	10.2	1.1	46.0	7.4	11.7	1.3	18.2	50.0
11	Piscataquis	Greenville	H. M. Shaw Manufacturing Co	155	52.1	7.7	13.8	.4	10.0	3.6	2.0	.5	6.8	2.5
12	Aroostook	Houlton	Houlton Grange	75	354.7	33.0	16.1	4.3	77.6	36.0	16.5	.5	16.0	51.2
13	....do	Van Buren	D. Murray	105	755.9	146.8	20.8	.8	159.2	12.1	21.0	39.0	30.5	129.6
	Average				201.3	21.0	13.8	1.8	42.9	8.4	14.4	6.0	20.5	28.9
	Average of 7 samples of granite waters				218.7	45.7	15.2	2.7	33.4	4.6	23.4	5.5	18.7	45.2

The table shows that the total solids found in slate waters in Maine range from 50 to 750 parts per million, the lowest proportion being in the hard metamorphic slates of western and southern Maine, and the highest, as a rule, in the calcareous slates of Aroostook County. The silica ranges from 6 to 21 parts per million, but does not seem to hold any definite relation to locality. Iron is nearly always absent, but the solids include some alumina, and the figures for iron and aluminum oxides range from 0.4 to 4.3 parts per million. The most variable constituent, with the exception of chlorine, is probably calcium, which ranges from 7 to 159 parts. As calcium is the principal constituent of lime, its amount is rather closely associated with the proportion of lime in the rocks, and the waters having the most lime are, as a rule, the hardest. The hardness is also dependent to a certain degree on magnesium, which ranges from 2.4 to 36 parts per million. Sodium ranges from 2 to 27 parts, potassium from 0.5 to 39, and chlorine from 2.5 to 130. The average composition of the slate waters of Maine, as calculated from these analyses, is given in the table. It will be seen that a slate water with an average composition would contain 201 parts per million of total solids and 43 parts per million of calcium, which would seem to be a rather soft water.

In order to compare the composition of slate water with that of granite, the average composition of granite waters as represented by seven analyses from different parts of the State is given at the foot of the table. It will be seen that while granite contains on an average more soluble mineral matter than slate does, the amounts of calcium, magnesium, and sulphates in slate are considerably higher than they are in granite. Hence slate waters, if the above analyses can be taken as representative, may be said to be, as a rule, somewhat harder than granite waters, though some slate waters which do not contain the sulphates and carbonates of calcium and magnesium are very soft. No tests for hardness were made in any of these analyses.

COST OF DRILLING.

The cost of drilling in slate is not so great as in granite and other crystalline rocks, and there is little reason why drilled wells in slate should not be preferred to dug wells. In Aroostook County, where the rocks consist of rather soft slate, the cost is only about $1 a foot, the well being cased to rock and the casing being furnished by the drillers. In Penobscot County the charge is generally about $3 a foot for the first 50 feet, $4 for the second 50 feet, and $5 for every foot below 100. In the more wealthy of the summer-resort regions drillers are likely to charge more, and on the islands a higher charge is necessary owing to the additional expense of getting machines and fuel across the water. The speed of drilling varies according to the hardness of the slates. Generally 2 to 10 feet a day can be accomplished, but one well is reported to have been sunk 35 feet in a single night.

SUMMARY.

Plenty of water of excellent quality can be found in most of the types of metamorphic slate that occur in Maine. This water may be found almost anywhere within the first 500 feet below the surface. The largest supplies are found generally between 200 and 300 feet, but abundant water for a family of ordinary size is usually to be had within 100 feet from the surface. The deeper wells are recommended wherever they are practicable, as they are safer from pollution. The cost of drilling wells in slate is less than in any other kind of rock in Maine, and a drilled well will always be cheapest in the end. The composition of slate water is uncertain, but the water is always excellent for drinking, and, except in a few regions where there is considerable lime in the rock, it is not too hard for boilers and causes very little scale.

OCCURRENCE AND COMPOSITION OF WELL WATERS IN THE GRANITES OF NEW ENGLAND.

By Frederick G. Clapp.

INTRODUCTION.

From time immemorial it has been commonly believed that an available supply of water does not exist in granite. This belief, though erroneous, appears to be well founded when it is considered that granite is one of the hardest rocks and that where it is exposed at the surface it is usually very solid and free from pores or crevices in which water might be held.

Until within the last few years few wells had been drilled in crystalline rocks. The conditions of the occurrence of water in such rocks have thus been little understood, and it has not been generally recognized that in many places they are traversed by numerous cracks along which water penetrates and in which it is held.

The literature bearing on this subject is scanty, but Ellis [a] has described the conditions under which water exists in crystalline rocks in Connecticut, as found during an extensive investigation of the underground waters of that State. The information obtained was of great practical value, as it showed that plenty of water exists in these rocks, although its presence or absence at any particular spot can not be predicted. Of two wells that are drilled side by side, one may be a failure and the other a success.

Field work by the writer in eastern Massachusetts and southern Maine in 1906 furnished considerable additional information regarding deep-well waters obtained in granite, a rock which covers large areas in these States.

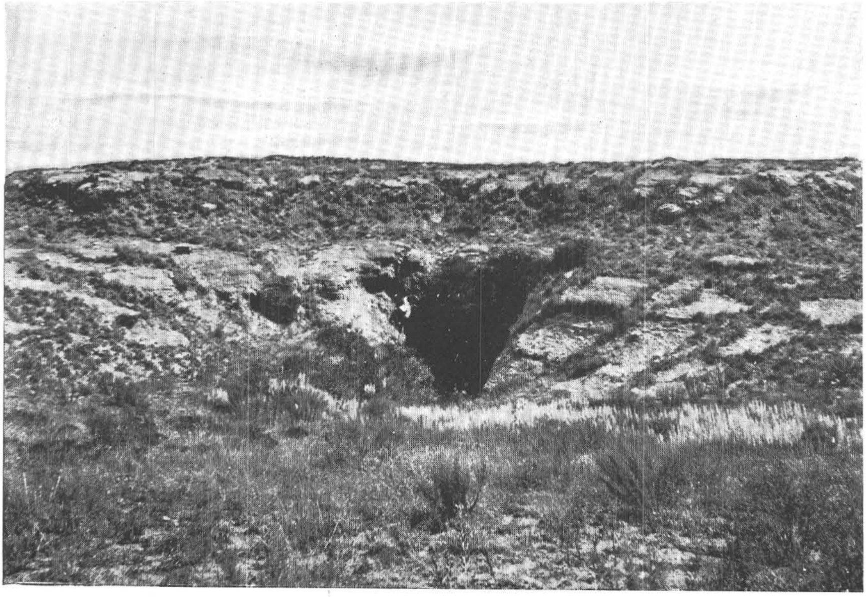
CHARACTER OF MAINE GRANITES.

Granite varies in character. The most common variety consists of a moderately coarse-grained, light-colored crystalline rock, composed of quartz, feldspar, and mica or hornblende. Granite ranges

[a] Ellis, E. E., Occurrence of water in crystalline rocks: Water-Supply Paper U. S. Geol. Survey No. 160, 1906, pp. 19-28.

A. WATER IN SHEET JOINTS IN GRANITE.

(See p. 41.)



B. SINK HOLES CONNECTED WITH UNDERGROUND DRAINAGE.

(See p. 49.)

in texture from a rock so fine that the grains are barely perceptible to a coarsely crystalline graphic granite (pegmatite), composed of crystals measuring several inches across. The rock commonly quarried as "black granite" is really a diorite. Many varieties of granite are found in Maine, but the one which covers the largest areas and in which most of the wells sunk in granite have been drilled is of moderately coarse texture. In many places it grades into the banded variety known as gneiss, and as the conditions that allow the penetration of water in gneiss are similar to those in granite, gneiss is included in the following discussion.

OCCURRENCE OF WATER IN GRANITE.

All rocks are traversed by numerous fissures or joint cracks, and these openings contain practically all the water that is found in granite. Most of the fissures are arranged in systems having a fairly constant trend, but there are also many that do not belong to any regular system. Some fissures are approximately vertical and extend many hundred feet in one direction, and along them water may find its way downward from the surface.

The vertical joints, though not at all regularly placed, are commonly 10 to 20 feet apart. They trend in all directions, but in most regions the greater number fall into a series which has a fairly constant direction or strike. These joints stand vertically or at steep angles ranging up to 30° from the vertical. There are also abundant cracks approximately parallel with the surface, as horizontal or sheet joints. These range from a few inches apart near the surface to many feet apart at a depth of several hundred feet. In a well at Stonington, Me., 27 distinct fissures from a few inches to 14 feet apart were passed in sinking to a depth of 94 feet.

Water may be held in sheet joints until it is tapped by a well, or it may find its way downward toward some adjacent lower ground. The occurrence of water in joint cracks is shown in Plate I, *A*, which illustrates a granite quarry at North Sullivan, Me. The more nearly vertical joints serve as channels for admitting the water from overlying surface deposits, and the sheet joints form reservoirs in which it is stored.

As most of the joints in granite are mere seams, the amount of water contained in them is necessarily small. Occasionally as much as 30 gallons a minute has been obtained with a steam pump, but in most wells the amount yielded is not over 10 gallons a minute.

On account of the great irregularity of the spacing of joints in granite, the success of any well in this kind of rock is wholly a matter of chance, dependent on whether the location is a fortunate one with respect to the arrangement of the joints. Figure 13 shows how a well may be sunk several hundred feet without striking a single joint crack, and in such a well no water will be found. More often many joint cracks are cut by the well. Where they are numerous an increased amount of water may be found by deeper drilling, but instances have been known where continued drilling struck an open

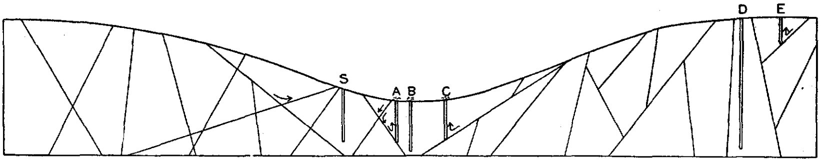


FIGURE 13.—Conditions of wells in jointed granite. A and C, Conditions under which flowing wells may be obtained; B, D, and S, conditions under which no water may be found; E, normal condition of obtaining water in drilled wells; A, conditions under which well may be polluted by drainage entering joint cracks near mouth of well.

crack in which the water was lost. Such uncertainty of results is one of the characteristics of well drilling in granite and similar rocks. Of two wells drilled within 50 feet of each other one may be a failure and the other a marked success, the result depending on whether or not a water-bearing fissure is struck.

PROPORTION OF SUCCESSFUL WELLS.

An effort has been made to obtain accurate information regarding the proportion of wells drilled in granite which are successful. Such an estimate is difficult to make for several reasons. Most well drillers are inclined to be optimistic and report few if any failures; failures are also apt to be forgotten by residents of a community; engineers, well drillers, and well owners do not agree as to what really constitutes a sucessful well; finally, a well that may properly be called successful where but a small water supply is needed is a failure if a large amount is required. The United States Government has abandoned wells in the East because the supply was only 10 to 20 gallons a minute, and in the irrigating communities in the arid States wells that yield even 200 or 300 gallons a minute may be called failures because 400 or 500 gallons is required to make the enterprise successful. For ordinary domestic purposes in the Eastern States 1 or 2 gallons a minute will usually suffice for a single family, but if less water than this is obtained the well is generally ranked as a failure.

A few experienced drillers report one or two wells out of a hundred that do not yield sufficient water. Sometimes there is a disagreement between the driller and the owner, owing to the fact that the well produced a fair amount of water when the vein was first struck by the drill, but later the water gave out. For this reason some of the more experienced and reliable drillers will not leave a well until a sufficient time has elapsed to determine whether or not the supply will be permanent.

It is difficult to decide what really constitutes a successful well. In the following table a successful well is considered as one which supplies enough water for ordinary domestic use, generally about a gallon a minute. In compiling the table all wells more than 50 feet deep in which the rock was known to be granite were considered, but it has been necessary to omit a few wells whose yield is not known. These are mainly wells that have been long abandoned, owing to installation of public supplies or to other causes. The unsuccessful wells include both those in which little water was found and those in which it was of inferior quality. All known instances of inferior quality of water from wells sunk in granite are due to the influx of sea water.

Relative success of wells sunk to different depths in granite.

	Number of wells with depth of—					Total wells.
	50-100 feet.	100-200 feet.	200-300 feet.	300-400 feet.	Over 400 feet.	
Yield (gallons per minute):						
1 to 5	7	5	2	2		16
6 to 10	5	1				6
11 to 50	6	7	5			18
Over 50	1	1	1			3
Successful; yield not known	19	6	3		1	29
Too little water	2	2	3		1	8
Water not usable			1	1		2
Total wells	40	22	15	3	2	82
Per cent successful	95	91	73	67	50	87

By a study of the table it will be seen that 87 per cent of the wells drilled in granite of which records are available were successful enough for ordinary domestic use. The other 13 per cent were wells in which water was absent or insufficient in quantity, or in which it was not usable because the wells were drilled near the ocean and salt water entered them along the open joint cracks. Of 72 successful wells only 3 were reported to produce over 50 gallons of water a minute.

WATER SUPPLY AND DEPTH.

There seems to be a general belief that where water occurs it increases in quantity with the depth of the well, and some people suppose that water may be found anywhere if a well is only drilled deep enough. This belief, however, is incorrect. Although water can usually be found by drilling in granite, it may not exist at a depth of several hundred feet. The joint cracks and other fissures in the rocks close at a great depth, owing to the pressure, and hence they can hold no water.

In the investigation of underground waters in crystalline rocks in Connecticut, previously referred to, Ellis found that below a depth of 200 feet the chances of obtaining water greatly decrease. The same conclusion has been reached in a study of the granites of Maine, but it is not found to be true of all rocks. One of the most experienced well drillers in Maine informed the writer that the maximum depth to which it is advisable to drill in granite is 185 feet, below which the chances of striking a supply of water decrease. This estimate was based on the results of all the wells sunk by him and agrees with the facts indicated by the foregoing table. By far the greater portion of wells drilled in granite to a depth of more than 50 feet do not exceed 100 feet. About half of those deeper than 100 feet do not exceed 200 feet, and only two granite wells are known to be more than 400 feet deep. The most important figures in the table are those showing the percentage of successful wells. To summarize these figures it may be stated that the chances of obtaining a good water supply by drilling in granite range from 95 per cent for wells less than 100 feet deep to only 50 per cent for wells more than 400 feet deep. Below 200 feet the chances of success decrease very rapidly, and those who drill below this depth take the risk of incurring more expense than would be involved if they should stop drilling and sink another well 50 or 100 feet distant.

The same conclusion is reached by a study of the following table, which shows the relation of the principal water vein to the depth of the well. From the totals it will be seen that of 47 wells in granite, which record the depth to the principal water supply, in 17, or over one-third, it is found within 50 feet of the surface; 16 more, or over half the remainder, reach it within 100 feet of the surface; 7, or half the recorded wells over 100 feet deep, obtain their principal supply from depths of 100 to 150 feet; 3 more get it between 150 and 200 feet; and 4 wells, or half of the wells more than 200 feet deep of which records are available, get their most important water vein below 200 feet.

Relation of depth of principal water vein to depth of well.

Depth of well (feet).	Number of wells in which depth to principal water vein (in feet) is—					
	0–50.	50–100.	100–150.	150–200.	200–250.	Total.
50–100	13	13				26
100–150	2	1	5			8
150–200	1		2	2		5
200–250	1	2			3	6
250–300					1	1
Over 300				1		1
	17	16	7	3	4	47

COMPOSITION OF GRANITE WATERS.

In the investigation of the underground waters of Maine, over sixty 1-gallon samples were collected from wells in different parts of the State and were analyzed by Prof. F. C. Robinson, of Bowdoin College. Nine of these samples were collected from wells drilled in granite in Hancock, Lincoln, and Cumberland counties.

With two exceptions the amount of total solids in the samples ranges from 81 to 419 parts per million. The exceptional waters are those of a well at the glue factory at Vinalhaven, and of a well belonging to C. A. Sproul at Pemaquid Beach. As both these wells are near the sea and as their waters are high in minerals in the proportions which would be expected where well water was mixed with ocean water, there is believed to be such a mixture in these wells and they were discarded in compiling the subjoined table. The seven remaining analyses are given in the order of the depth of the wells, which ranges from 25 to 279 feet. Comparison of the constituents shows no relation between the depth of the well and the proportions of any of them.

The average composition of granite water, as given in the table, is the average calculated from the seven analyses. With several of the constituents this average is considerably higher than the most common composition, for the reason that one or two exceptionally high figures raise the average. Granite water, when not contaminated by surface drainage, is excellent for drinking and is probably satisfactory for every ordinary use. A comparison of the average composition of granite waters with the average composition of slate waters calculated from 13 analyses shows that the former contain a somewhat higher amount of total solids. Slate waters are, however, the harder, as shown by the greater amount of calcium and magnesium, which are probably present mainly as carbonates and sulphates. No tests for hardness were made in these analyses.

Composition of granite waters from drilled wells in Maine.

[F. C. Robinson, analyst. Quantities in parts per million.]

No.	County.	Locality.	Owner.	Depth (feet).	Total solids.	Organic and volatile matter.	Silica (SiO_2).	Iron and aluminum oxides (Fe_2O_3+Al_2O_3).	Calcium (Ca).	Magnesium (M_3).	Sodium (Na).	Potassium (K).	Sulphate radicle (So_4).	Chlorine (Cl).
1	Hancock	North Sullivan	J. M. Blaisdell	25	195.7	26.9	8.3	4.7	37.4	4.3	25.6	5.6	14.9	41.2
2	....do	....do	Crabtree & Havey	51	364.3	66.7	12.5	2.1	62.4	3.4	61.8	3.7	16.0	140.0
3	Lincoln	Waldoboro	Miss E. F. Genthner	56	418.9	99.5	10.9	3.5	56.6	9.0	29.5	13.0	36.0	56.6
4	....do	Damariscotta Mills	G. W. Waltz	64	129.0	29.0	23.8	2.5	18.1	2.9	13.1	5.8	13.6	15.0
5	Hancock	Greeninge Island	J. G. Thorp	88	81.4	5.2	8.5	1.1	1.1	1.8	11.0	1.7	14.7	23.1
6	Cumberland	Bridgton	J. K. Martin	125	205.5	74.0	31.1	2.8	28.9	7.6	9.6	6.9	9.6	23.5
7	Hancock	Stonington	J. C. Rogers	279	136.5	18.6	11.2	2.0	29.3	3.4	13.0	1.9	25.9	16.9
	Average composition			....	218.7	45.7	15.2	2.7	33.4	4.6	23.4	5.5	18.7	45.2
	Average composition of 13 samples of water from slate			....	201.3	21.0	13.8	1.8	42.9	8.4	14.4	6.0	20.5	28.9

COST OF WELLS IN GRANITE.

As granites and gneisses are among the hardest rocks known, drilling in them is difficult and expensive. Generally the well is not deepened more than 3 to 5 feet a day and sometimes only a few inches. The cost is necessarily an important factor in the sinking of wells. It not only varies with the kind of rock, but with locality and other conditions. The price for drilling 6-inch holes in granite on the coast of Maine ranges from $4 to $6 a foot, the higher figure being the more common. Most drillers charge about $1 a foot more for drilling on the islands than they do on the mainland.

A significant fact is brought out by comparison of the cost of drilling granite wells and the cost of blasting open wells in granite. In some parts of Maine $6 a foot is the rate charged for either of these methods. A blasted well is necessarily limited to a few feet in depth and is open to the chance of pollution through surface drainage, which may easily enter it. Both these objections are less applicable to a drilled well, which is therefore to be preferred as a permanent investment.

SUMMARY.

To summarize, it is safe to say that under the conditions which prevail in the New England States about 90 per cent of the wells drilled in granite will find enough water to supply the domestic needs of a family. In about 85 per cent enough water will be found within 100 feet of the surface. A well should not be abandoned without sinking at least 200 feet, but drilling deeper than 200 feet is not advisable, although a few wells have procured water at greater depths. If a well owner does not obtain sufficient water at 200 feet, he is advised to sink a second well 100 feet or more distant, and the chances are good that the second attempt will be successful.

Although granite water is moderately charged with mineral matter, it is not hard and is known not to contain sufficient mineral matter to interfere with its use.

POLLUTION OF UNDERGROUND WATERS IN LIMESTONE.

By George C. Matson.

INTRODUCTION.

With increase in density of population the maintenance of the purity of water becomes a matter of vital importance. In a few places it is possible to procure supplies which have moved long distances through beds of sand capped by clay or other impervious materials. Such supplies are essentially free from pollution because whatever polluting matter they may have contained has been removed by the natural filtration they have received in their passage through the sand. Unfortunately, however, in many localities it becomes necessary to use supplies which receive little or no natural filtration. In such places it is necessary either to prevent pollution or to resort to some method of artificial purification. Even the most ardent advocates of filtration will admit that the purification of polluted water must always be more or less imperfect. For this reason it becomes desirable to prevent pollution, and this can be accomplished only when the source of the polluting matter and the methods by which it reaches the water are thoroughly understood.

In limestone regions where the country rock is covered by a thin mantle of residual materials the dangers of pollution are very great, and there is practically no opportunity for natural purification. The danger is enhanced by the fact that persons using underground water are apt to rely on its appearance and temperature as indications of purity. It is generally considered that water which is clear and cold is pure, but no such conclusion is warranted, for some of the most dangerously polluted waters are free from sediment and as cool as ordinary well or spring water.

OCCURRENCE OF WATER IN LIMESTONE.

Pores.—In order to understand the manner of pollution in limestone it is necessary to review briefly the mode of occurrence of underground water in such rocks. A few limestones are sufficiently porous to absorb much moisture, but most of them, especially those in the older geologic formations, are too dense to absorb water. In this paper the porous limestones will not be considered, the discussion being confined to those limestones which yield water from more or less open passages.

Joints.—Limestones are usually traversed by at least two sets of vertical joints, making approximately right angles with each other. Other partings at right angles to these joints form the bedding planes of the rock. The spacing of joints is fairly uniform over considerable areas, and the interval is commonly to be measured in feet, though where the rocks have been deformed the number of joints is increased. The bedding planes usually show little uniformity of arrangement, and an interval of a few inches may be followed by one of much greater magnitude.

Caverns.—The water which comes from limestones usually makes its way along enlarged joints known as caverns. The enlargement is due to solution of the limestone by water containing carbonic acid. Obviously the places where water circulates most readily will, other things being equal, suffer the greatest loss by solution, but differences in the solubility of the rock may offset the effect of rapid circulation.

Doubtless the most common locality of rapid solution is at the intersection of a prominent bedding plane and a more or less open joint. Owing to the presence of numerous open joints or to the solubility of the rock, very large chambers, called domes, are formed in certain places where a considerable amount of water enters the underground channel. This water, coming fresh from the surface, is armed with a great amount of carbonic acid and attacks the limestone about the point of entrance. As it flows farther and farther from this point it loses its power to dissolve, because it has gradually picked up as large an amount of calcium carbonate as it can carry.

The belt of rapid solution is limited to the zone of active water circulation, and the formation of caverns therefore takes place largely above the level of the surface streams which receive the underground drainage, but this does not imply that there is no deep-seated solution nor that active circulation may not in some places extend slightly below the level of surface drainage.

Sink holes.—As solution progresses some parts of the cavern roof become so weakened that they collapse, forming sink holes (Pl. I, *B*, p. 40). If the channel beneath the point of collapse is large in proportion to the amount of material which falls, the sink is an open hole; but if the amount of fallen material is sufficient to clog the channel, the sink appears as a rounded depression which has no outlet. The fallen material may obstruct the opening so that the stream appears at the surface, or it may leave a passage which will allow the drainage to continue underground. In this event the gradual wearing of the stream may remove enough of the fallen material to form an open sink.

UNDERGROUND STREAMS.

RELATION TO SURFACE DRAINAGE.

Downward migration.—In the process of deepening its valley a stream lowers the base level of its tributaries and thus affords them an opportunity to degrade their channels. When the tributaries flow in caverns they lower their channels along joint planes, and the process goes forward most rapidly along some particular lines, just as in the formation of the original cavern. At certain places where there is rapid downward movement from the old to the new channel more or less rounded openings are developed. These openings furnish a passage from the old to the new cavern and are usually called pits. They often form beneath the domes mentioned above, their

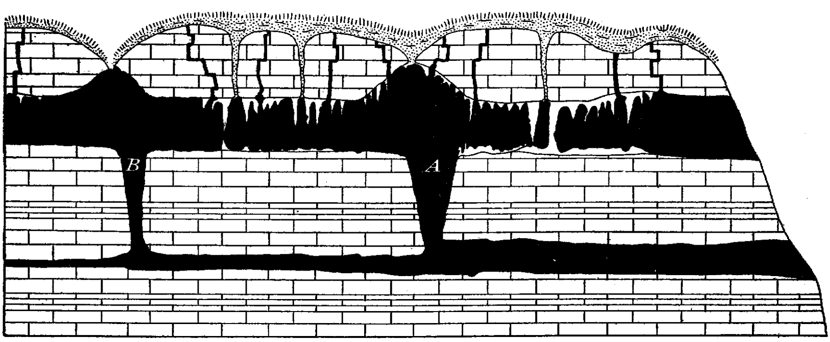


FIGURE 14.—Cavern showing different levels of underground streams.

location being determined in part by the presence of initial crevices and in part by the same condition which produced the domes, namely, the entrance of surface water bearing considerable free carbonic acid. (See *A*, *B*, fig. 14.) Doubtless the formation of both pits and domes is aided by the mechanical action of the water, especially where it contains sediment. As long as the lower channel or the passages leading to it are comparatively small the old cavern retains a large part of the drainage. With the enlargement of the new cavities the old channel receives less and less of the original drainage until it is entirely deprived of its original headwaters except during storms, and at last, when the new channels have become sufficiently enlarged, the old channel receives only the drainage of its local tributaries.

Migration from higher to lower levels may take place at successive intervals, leaving a series of abandoned channels at different levels. The course of the underground stream at each successive stage probably deviates more or less from the course of the abandoned channel.

Moreover, the course may not lie in a single channel, but passages may divide and subdivide, forming a more or less extensive network of channels.

Effect of shale beds.—If a shale bed is encountered by the water in its downward progress a cavern is usually formed above it, and if the shale bed is a considerable distance above the level of the surface stream which receives the drainage from the cavern the water may emerge from the cliff above the surface stream. The mechanical wear of the underground stream may remove the shale at some point and thus permit the formation of another channel nearer the level of the surface stream. If the shale bed is of considerable thickness the downward migration of water may be permanently obstructed. The lowering of the surface streams usually takes place much more rapidly than the lowering of the underground streams. In consequence of this fact the underground streams may remain considerably above the level of the surface stream, even where there are no beds of shale or other dense material to prevent downward migration.

Change from an underground to a surface stream.—The numerous points of weakness in the roof of an old cavern may result in the development of a line of sink holes, which serves to indicate the course of underground streams. As the work of undermining the roof progresses the coalescing of the sink holes may give an open channel for a considerable distance.

If this happens at the lower end of the underground stream a gully is formed with a large spring at its head. This explains the common occurrence of springs in such situations rather than along the valleys of the large surface streams. A segment of the roof of a cavern may fall and the water, after emerging as a spring and flowing for some distance as a surface stream, may reenter its underground channel through an open sink. Sinking streams are very common in limestone regions. Where all but a small section of the roof of the underground channel falls the section still left standing is known as a natural bridge.

TRACING UNDERGROUND STREAMS.

Because of the great complexity of the underground drainage the tracing of underground streams is a task requiring the exercise of considerable patience. If it is possible to enter the underground channels, a survey may be made; but most of these channels are inaccessible and some other method must be used. The common methods of tracing such streams may be grouped under two heads—chemical and physical.

Chemical tests are made by dissolving certain materials in water and introducing them into the underground stream either directly through open holes or by seepage through the soil. The compounds most commonly used are chlorides of sodium, calcium, or ammonium, nitrate of potassium, and salts of aluminum or iron. After the introduction of one of these substances chemical tests are made at frequent intervals to detect its presence in samples taken from the well or spring that is supposed to receive water from the underground stream.

Physical tests are made either with coloring or suspended matter. The coloring materials commonly used are potassium permanganate, fuchsine, Congo red, methylene blue, and fluorescein. Suspended matter may be of either microscopic or megascopic size. Such substances as flour, starch, or cultures of bacteria may be introduced into the water of the underground stream and the suspected spring or well water examined to determine their presence or absence. For microscopic tests wood, sawdust, leaves, oil, and many other substances are used.

The choice of the material for tests will depend largely on the local conditions. Oil and other substances which float on the water are satisfactory only where there are no quiet reaches of water and no marked constrictions in the channel to delay their progress. In some experiments they have proved satisfactory; in others they have given negative results. They are useful in connection with chemical or with other physical tests because they give an idea of the character of the underground stream.

In one test oil, fragments of wood, and common salt ($NaCl$= sodium chloride) were used in a single underground stream. The materials were put into the stream through an open sink about one-eighth of a mile from its point of emergence in a spring. The oil appeared at the spring in one hour and the salt in seven hours; the wood fragments had not appeared after a lapse of several days. The writer has found salt very satisfactory for testing streams having a flow of several million gallons or less daily, but its use would be impracticable in very large streams such as are found in some caverns.

DEPOSITS IN CAVERNS.

After the abandonment of a section of the underground stream the amount of water entering the old channel becomes less and less until it is confined largely to small seeps. At this stage much of the water is removed by evaporation and the process of solution gives place to that of deposition. At first deposition is rapid because the crevices are large enough to supply all the water that can be evaporated, but gradually as the points of ingress become closed by deposition the amount of water entering diminishes until finally it may cease altogether, leaving a portion of the cavern dry. Although the greater part of the deposition in caverns takes place after the active work of solution has ceased, the two processes may go on at the same time and there is always a gradual transition from one to the other.

The products of deposition are the stalactites, stalagmites, and various irregular masses which ornament caverns. These are always most numerous in the upper levels, though they may form to some extent in all the underground channels.

POLLUTION OF LIMESTONE WATERS.

CHARACTER.

Suspended matter.—Certain waters may be rejected as unfit for use because they contain straw or other materials of organic origin, and the wisdom of such rejection is too apparent to need comment. On the other hand, the presence of sediment in water is often taken as an indication of the entrance of surface water through an open sink; such a conclusion, however, may be wholly erroneous.

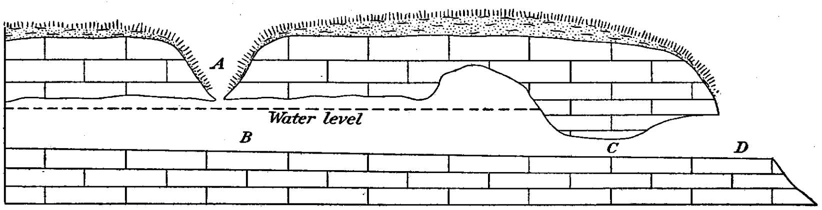


FIGURE 15.—Diagram of cavern showing how sediment may be deposited by the underground stream.

Figures 15 and 16 show that the presence or absence of sediment can not be considered a safe indication of the presence or absence of surface drainage. In the cavern shown in figure 15 sediment-laden surface water entering at *A* may be so retarded in the chamber *B* that it deposits its sediment and passes through a constricted channel, *C*, to emerge at *D* comparatively free from sediment.

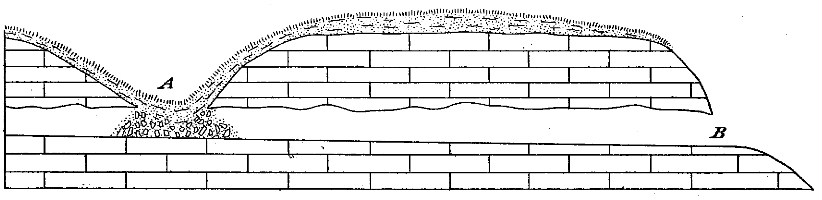


FIGURE 16.—Diagram of cavern showing how sediment may be obtained by the underground stream.

This water, though comparatively clear, may contain a large amount of surface drainage in some other form. In the cavern shown in figure 16 the water may obtain sediment at the closed sink *A* and emerge at *B* so turbid as to indicate a direct connection with surface drainage.

The conditions represented by these two figures are transitory, for in the cavern of figure 15 the chamber *B* will soon become partly filled with silt, so that the water passing through the channel *C* will transport a considerable amount of sediment, and in the cavern of figure 16 the gradual removal of material from the sink *A* will soon form an open hole. Sediment may also be deposited in caverns during low-water periods and then washed out during high-water periods. Solutions of organic matter may be temporarily retained in underground sinks in the same way. It is always wise to refrain from drinking underground water which contains silt or clay, for although these materials in themselves are seldom injurious they may indicate the presence of surface drainage which has received little or no natural purification. It must not be inferred that all surface drainage is harmful; but it is well to bear in mind the possibilities of pollution by such drainage, and if any part of the surface drainage comes from a city or from dwellings the water should be rejected.

NATURAL PURIFICATION.

A fact which needs great emphasis is that water which flows in channels in limestone probably receives less natural purification than surface water. Especial attention is called to this fact, because there is a popular belief that water is purified by passing a short distance underground. This belief is based on a study of the purification of water by its passage through sand or sandstone. In these materials the purification is mechanical and takes place because the openings between the sand grains are very small. In other words, in removing the objectionable matter the sand acts as a mechanical filter.

Water that flows through channels in limestone receives no filtration, and consequently but little natural purification. It is also effectually sealed from the oxidizing effects of air and sunlight. The flow of water in limestone passages may be compared with its movement through ordinary water mains, and the chances for purification are about equal in the two channels.

EXAMPLE OF POLLUTION.

A typical example of the pollution of underground water in limestone is afforded by a certain city containing a spring which supplied several persons. The failure to realize the danger of pollution was due not to carelessness or negligence but to a belief that the water of the spring all came from points beyond the city limits. The important fact that underground streams have tributaries was entirely overlooked. Figure 17 gives the plan of the surface drainage of the area furnishing water to the spring *A*, which is located at the edge of the city. There are several sinks within the city limits, and the question to be decided was whether the spring received drainage from the city through these sink holes. The depressions which received the surface drainage, outlined in figure 17, appeared to be the result of the partial collapse of cavern roofs, this fact being indicated by their general rectangular arrangement and their relation to the joint planes of the limestone. The presence of the sink holes indicated underground drainage, and it was assumed that this drainage would follow more or less closely the lines of surface drainage. The general trend of this surface drainage is toward the spring.

To test the connection between the sinks and the spring, salt was introduced into some of the sinks and its presence noted in the spring. The sinks selected for the investigation were chosen because they were supposed to include between them nearly all the area in the city which drains to the spring.

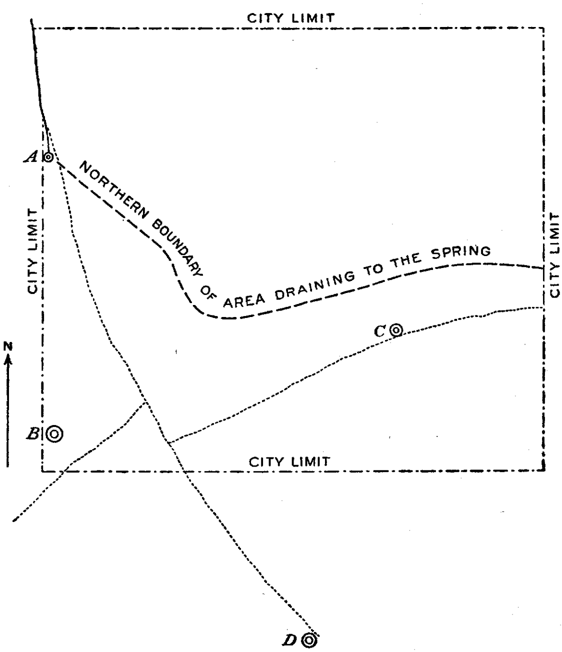


FIGURE 17.—Location of sink holes and springs.

The sink *B* is not open, and after a heavy rain it is occupied by a pool of water which seeps away rapidly. Four barrels of salt were put into this sink during a rain which lasted for twenty-four hours. Samples were then taken at the spring at intervals of one hour. The amount of chlorine in the samples was determined by means of standard silver nitrate tablets, potassium chromate being used as an indicator. Eight hours after putting the salt into the sink the amount of chlorine in the spring had doubled, and within the next two hours it rose to four times the original amount. It remained fairly uniform for several hours, finally falling to double the original amount and continuing nearly uniform for the succeeding forty-eight hours, when observations were discontinued.

The sink hole *C* had originally been open, but at the time the tests were made was filled with broken stone and loose earth. During heavy rains considerable water collected in this sink. It was drained by means of a small passage through the loose material. The water poured into this passage at the rate of 25 to 30 gallons a minute. Two barrels of salt were put into the water which had collected in this sink after a heavy rain, and tests were made at the spring in the same manner as before. At the expiration of sixteen hours the amount of chlorine in the spring had increased 100 per cent. It rose rapidly to nearly 150 per cent above the normal and then fell with corresponding rapidity until, twenty-four hours from the time the salt was put into the sink, the amount of chlorine in the spring was only about 50 per cent above the normal.

Similar tests were made in connection with the sink at *D*, but the results were not entirely satisfactory because only 1 barrel of salt was used. However, the general trend of the underground drainage is probably toward the spring and the location of the sink *D* indicates that it is, with little doubt, connected with one of the underground channels which supplies water to the spring.

The importance of this investigation is shown by the facts that the sink *B* receives all the drainage from two houses and a barn and that the sink *C* receives a large part of the drainage of more than a score of houses. None of these houses are connected with sewers, so that the danger of pollution is very grave. In the area between *B* and *C* are a number of dwellings and the drainage of some of them is allowed to enter sink holes.

RECOMMENDATIONS.

The practice of putting rubbish, barnyard filth, etc., into sinks should be abandoned. Still more reprehensible is the custom of running sewage into sinks, thus converting the underground channels into natural sewers. This practice, which is by no means uncommon, is often defended by the assertion that the water in limestone channels beneath a city is unfit for drinking even without the sewage. The correctness of this assertion can not be disputed, but there are persons who are ignorant of the danger and who continue to use the underground water. Moreover, those living at some distance from the city may use water from the underground channel which receives the sewage. For these reasons any city which proposes to convert an underground watercourse into a sewer should be forced to trace the channel to its destination so that others may be protected.

There is need of legislation to prevent the unnecessary pollution of underground streams. Such legislation has been enacted for the protection of surface water, but the protection of underground water has been entirely neglected.

PROTECTION OF SHALLOW WELLS IN SANDY DEPOSITS.

By Myron L. Fuller.

INTRODUCTION.

Notwithstanding the exceedingly unsanitary surroundings of the driven wells in certain sandy districts which have been investigated by the United States Geological Survey, the waters in many of these wells have been found to be reasonably safe. Investigation shows this safety is due to certain definite conditions, which are the result of known laws governing the movements of ground water. It is the object of this paper to discuss these conditions and to point out their application to the sinking of shallow wells in sands receiving polluting matter at adjacent points.

SANDY DEPOSITS.

GENERAL STATEMENT.

In the eastern and northern parts of the United States deposits of sand are very numerous, widely distributed, and of considerable area, and constitute the chief source of domestic water supplies at hundreds if not thousands of points. Part of the deposits have been formed by waves along the coasts, part by winds blowing the sands from beaches and other exposed sandy areas and building them into dunes, part by deposition in glacial streams, lakes, etc., during the ice age, and part by deposition along the courses of the present rivers and smaller streams. The glacial and alluvial deposits are among the most common sites of towns, and many of even the dunes and sea beaches are occupied by populous resorts, as along the Long Island and New Jersey coasts.

In sandy regions of the type described water is generally abundant, at least in the eastern part of the United States, and commonly occurs very near the surface. For this reason shallow wells are in general use, most of them being of the driven type, although open wells are used in some of the more unprogressive districts. This is especially to be regretted, as the open porous sand readily transmits sewage and other polluting matter, much of which enters the open well through the curbing. In tubular driven wells this matter is shut off from all except the bottom of the well, and to procure good water it is only necessary to drive to a moderate distance below the water table.

In the internal structure of sandy deposits, as determined by the character and arrangement of the materials, many variations exist, but the deposits can all be grouped under one or the other of two classes—sands of uniform character and sands with included impervious or relatively impervious layers, which need not necessarily be beds of clay, for layers of fine sand or even well-stratified layers of material of the same texture may act as confining beds.[a] The second class therefore is very large, and deposits of this type far outnumber those of the first class.

UNIFORM SANDS.

Deposits of uniform sand are limited in large measure to the wind-formed deposits known as "dunes," although certain of the more sandy glacial deposits closely approximate uniformity. The glacial deposits generally present a fairly uniform surface, but the dune areas are commonly irregular, though some rather flat-topped wind-deposited dunes are known. A smooth-topped gently sloping deposit is taken as a type in the following discussion for sake of

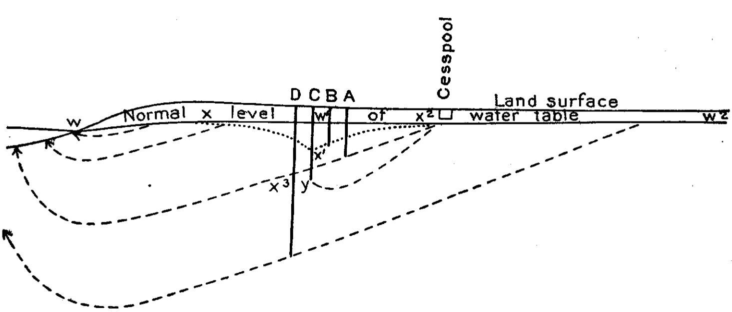


FIGURE 18.—Conditions of pollution in thick deposits of uniform materials.

simplicity. The conditions in a dune area of rolling topography would, however, be essentially the same, as the form of the water table in porous sands would be little affected by individual dunes, which are generally a minor feature of the topography.

The conditions to which wells are subject in uniform sands are illustrated in figure 18, in which the position of a cesspool and of the wells A, B, C, and D are indicated. The wells are assumed to be tubular and to draw water from the bottom only. The normal position of the water table is represented by $w\text{–}w^1\text{–}w^2$ and its position after pumping from well C by the dotted line $x\text{–}x^1\text{–}x^2$. The normal movement of the

[a] Fuller, M. L., Two unusual types of artesian flow: Water-Supply Paper U. S. Geol. Survey No. 145. 1905, pp. 41-45.

ground water is indicated by the broken lines extending diagonally downward from the water table and curving upward to points of emergence along the lake or watercourse at the left. Before any of the wells are pumped the sewage from the cesspool will follow approximately the line x^2–x^3. Under these conditions well A, which just penetrates to this line of flow, will be endangered by the polluted matter, but well B, which fails to reach the line of movement, and wells C and D, which penetrate to a point well below it, will probably be unaffected. If either of the wells is pumped vigorously the water table will be lowered in its vicinity. (Fig. 18 shows the effect of pumping well C.) The effect as regards contamination will depend on the amount pumped. Pumping well A will result in a lowering of the water table in its vicinity and an influx of water from below and from the downhill side as well as from the direction of the cesspool, but as an offset to the increased amount of pure water drawn in more sewage is likewise obtained. If well C is pumped but slightly, the quality of the water may be unaffected, but if pumped hard the water table may be lowered beneath an area extending to a point near the cesspool, the result of which will almost certainly be pollution of the well water. The effect of pumping this well, as shown in the diagram, is a lowering of the water table at the well from w^1 to x^1 and a change in the direction of the ground-water movement in its vicinity from x^2–x^3 to x^2–y, which will result in a pollution of the well. Pumping well D, though lowering the water table to a depth corresponding with x^3, will not result in pollution because of the much greater depth of the well.

Thus in uniform materials where the water is unconfined any considerable pumping of wells whose bottoms are near the lines of underflow from cesspools or other sources of polluting matter is likely to result in pollution of the well water; on the other hand, wells sunk any considerable distance below these lines of underflow are safe under ordinary conditions of pumping.

The "safety distance," as it may be called, has been the subject of much discussion. A common statement is that a well should not be located within a distance equal to one to five times its depth from any source of pollution. The application of any such rule may be far from safe, however, as an examination of figure 18 will show. The source of danger is not necessarily the nearest cesspool, but is quite as likely to be a more distant one. Well D, for instance, is safe from pollution from the cesspool shown, but would not be safe from a cesspool located at w^2.

It has been found that the depression produced in the water table by pumping has a diameter ranging from 15 to over 150 times the vertical distance which the water has been lowered, and some authorities assume that any polluting matter coming within the limits of this depression will find its way to the well. This is probably true of open wells in general, but it is not true of driven wells nor of tightly-cased drilled or bored wells. These, though protected from the entrance of polluting matter near the surface, are, as has been explained, not safe from pollution from distant sources. So many factors, most of which are variable and generally unknown, enter into the question of the depth at which a well is safe that no general rule can be laid down. Field observations, however, seem to show that where the bottom of the well is 10 feet or more below the position of the water table when lowered by pumping the water is generally pure. A larger margin of safety should, if possible, be allowed, especially where the well is to be subjected to heavy pumping or is in a thickly settled district where many cesspools or other sources of contamination exist.

NONUNIFORM SANDS.

In the class of nonuniform sands are included both deposits consisting of alternations of sands of different texture and deposits consisting of sands with interbedded layers of finer silt.

In deposits of this nature the conditions differ greatly from those existing in uniform sands. The active circulation, instead of reaching to a considerable depth, as in uniform sands (fig. 18), is, so far as need be considered in the present discussion, restricted to zones of moderate depth (see fig. 19), in which movement is relatively rapid.

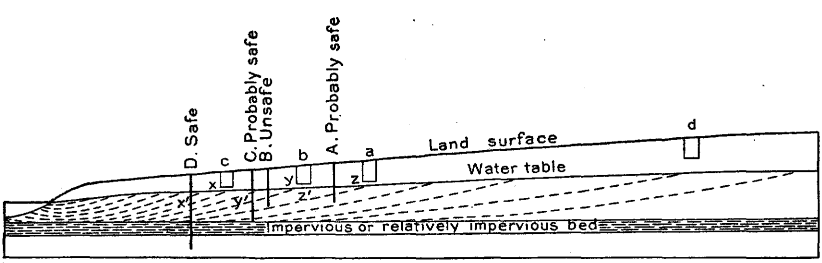


FIGURE 19.—Conditions of pollution in thin beds of sand overlying impervious layer.

The conditions shown in figure 19 may be taken as typical of those existing in nonuniform sands. The figure shows a bed of porous material overlying an impervious or relatively impervious bed, also a series of cesspools (a, b, c, d) and tubular wells (A, B, C, D) drawing water from the bottoms of the casings. The normal level of the water table is indicated and the ground-water movement is shown by broken lines. Before the wells are pumped or when only slight amounts of water are raised the ground water is essentially undisturbed and the movement of sewage from the cesspools will be approximately along the lines x–x′, y–y′, and z–z′. Under these conditions well A is probably safe, as it extends below the line of movement from cesspool a. Well B, however, although of the same depth as well A, is probably unsafe because of the greater depth reached at that point by the polluting matter from a. At the same time well B is probably safe from pollution from cesspool b, showing again that it is not always the nearest cesspool that is the source of contamination.

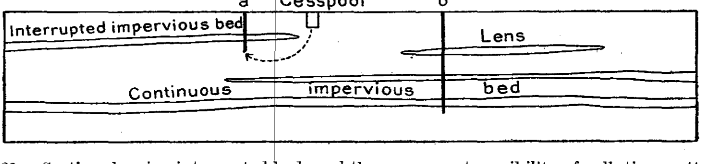


FIGURE 20.—Section showing interrupted beds and the consequent possibility of polluting matter passing underneath impervious beds.

Well C, close to well B, by going deeper obtains water which is probably safe from cesspools a and b but might be polluted from a more distant source, as a cesspool at d, although the distance may be so great that all danger is eliminated. To guard against possible pollution a well should be sunk below the first impervious bed (as at well D), but even this will not always insure safety, as in many places the impervious beds are not continuous but thin out, as shown in figure 20, so that polluted waters can pass underneath them. Well b, in figure 20, passes below a continuous impervious bed and would be safe. Figure 20 also shows why the succession of beds in closely adjacent wells may be dissimilar and why the encountering of similar beds at the same depth, as at a and b, does not prove continuity.

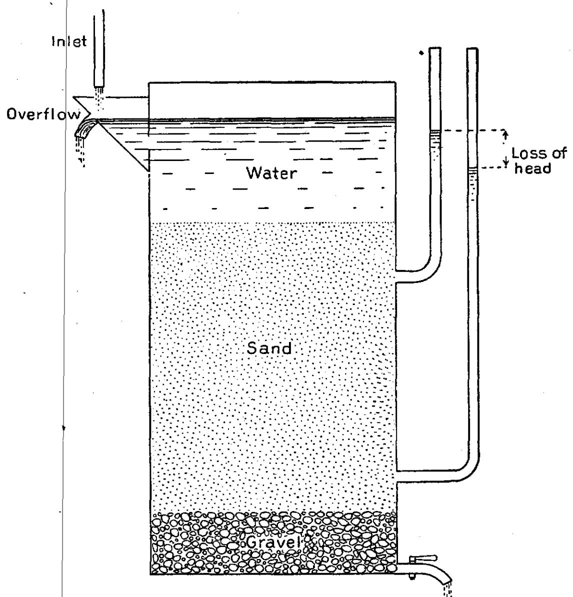


FIGURE 21.—Diagram showing loss of head by friction in column of sands. (After Hazen.)

MOVEMENT OF GROUND WATER.

Figures 18 and 19 show that water while sinking a certain distance downward spreads out to a much greater horizontal distance. That the movement is much more rapid near the surface than at greater depths will also be apparent from a study of the conditions of motion. The flow of water through a soil of given texture at a fixed temperature and depth is proportional to the difference between the pressure head at that depth and that at the surface of the water table. The head at any deeper point will be diminished owing to the friction caused by the material between the two points. This is brought out very clearly in figure 21. The velocity of the ground-water body near the level of the water table may be many times greater than at depths of even no more than 50 or 100 feet. In fact it is probable that in many valleys and basins, especially where the materials are open and porous,

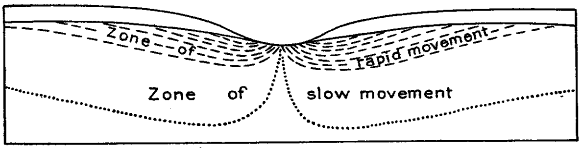


FIGURE 22.—Diagram showing concentration of motion in upper part of ground-water body.

the ground water below the level of the surface drainage is relatively stagnant, the increment due to rainfall being almost entirely removed by movements in the upper portion of the ground-water body, as shown graphically in figure 22.

The principle outlined is of great importance in considering the pollution of wells. It means that polluting matter may be carried in the upper portion of the ground-water body with greater rapidity and to a greater distance than in the portion a few feet farther down, and this suggests deepening tubular wells as a precaution against contamination.

NATURAL FILTRATION.

Types.—So-called natural filtration has been much discussed in recent years, and more or less definite ideas of its supposed applications exist in the minds of people in general as well as in those of scientists. Everyone has observed and is familiar with the effects of filtration in removing visible impurities from liquids, and many have been inclined to the belief that bacteria and even matter in solution could be removed in the same way. There are, however, for the most part, very slight grounds for such belief.

Natural filtration may be subdivided according to the character of the supposed action into mechanical, chemical, and bacteriological filtration. These are briefly considered in the following paragraphs.

Mechanical filtration.—The removal of matter held in suspension in the water constitutes mechanical filtration and is due mainly to the entanglement of the suspended particles among the grains of soil or other filtering medium through which the water passes. The efficiency of this process depends on the size and uniformity of the grains, on the pressure head of the water which is passing through the soil, on the temperature of the water, etc. The slower the filtration the more effective it will be, hence fine material is more effective than coarse, mixtures more efficient than uniform materials, and low-pressure heads and low temperatures better than high ones.

There is no chemical purification in filtration of this nature, and in ordinary materials and with waters free from sediment there is but a relatively small decrease in the number of bacteria. Where sediment of any sort is present in considerable amounts, however, many bacteria are entangled in the filter and remain behind with the residue. Although the number thus removed may amount to a considerable proportion of the whole, if the water was originally polluted, there are almost invariably enough bacteria left to render it unsafe for drinking.

In artificial mechanical filtration through stone or other very dense media fairly perfect removal of bacteria has been effected, but under the conditions existing in nature such removal will rarely take place, except where the water passes for a long distance through fine materials. But even if bacteria will not pass through a filter with the water, they may in the course of time spread through it by multiplication, finally contaminating the water on the other side.

Chemical action.—Chemical changes in waters passing through soils are the result not of any mechanical filtering but of reactions between the water and the material with which it comes into contact. In shallow ground waters the process, instead of being one of purification, is generally one of mineralization, material being taken up from the soil instead of being left behind in it. Purification through chemical deposition is usually accomplished only at considerable depth below the surface, beyond the reach of the ordinary shallow wells. Iron, however, is occasionally deposited in small amounts between grains of sand, etc., along the contact with underlying clayey materials, even near the surface. In general the mineral matter dissolved by shallow waters is small, but in the alkaline lands of regions of slight rainfall it may be very great.

So far as the sanitary effect is concerned the most important chemical action accompanying filtration through soil is the oxidation of polluting materials. Oxygen (in air) is everywhere present in soils above the water table and, either by direct chemical action or through the influence of bacteria, attacks and breaks down the impurities, reducing them to harmless mineral compounds.

Bacteriological action.—Even more important than the oxidation of impurities by the aid of bacteria is the work done by the so-called nitrifying bacteria, which not only break down the organic polluting materials but destroy most of the disease-producing organisms. Under artificial conditions, as in filtration plants, the action is almost perfect, 99.5 per cent or more of the dangerous bacteria being removed; under natural conditions, however, only a relatively small fraction of the germs are affected.

General effect.—In summarizing the preceding paragraphs it may be said that in natural filtration through a moderate depth of soil the suspended impurities are in large part taken out, parts of the remainder are oxidized and their odors destroyed, and many of the bacteria are removed. The water is clear and sparkling, but as a rule it still contains unoxidized polluting matter and sufficient bacteria to make it unsafe for domestic use, except where the wells are remote from the source of pollution. The "safety distance" depends on a large number of factors, including the nature and porosity of the soil, the velocity and direction of ground-water movement, the number of sources of contamination, and the amount of pollution entering the ground.

SUMMARY AND CONCLUSIONS.

The alternation of layers of materials of different texture, even if all are pervious, and the presence of stratification planes in uniform materials tend to obstruct the downward passage of water and to confine pollution to the upper portion of the ground-water body—the part immediately below the water table. This explains why many towns located on sand deposits procure unpolluted water from driven wells sunk a few feet below the ground-water level, notwithstanding the sands receive the entire drainage of the towns. To this fact is due the absence of typhoid, cholera, and other water-borne diseases at many points where danger from pollution might be supposed to exist. To insure safety wells should be carried to a considerable depth below the ground-water level, and as each succeeding layer of material affords additional security they should be sunk as deep as possible.

Polluted ground waters are more or less purified through the removal of their suspended matter and a portion of their bacteria by entanglement among the grains of the material through which they pass, by oxidation, and by nitrifying bacteria, but more or less polluting matter remains for a considerable length of time.

The distance to which pollution is carried will depend on the porosity and size of grain of the materials through which it passes, the amount of rainfall, the inclination of the surface and the elevation of the outlet, the temperature, the number of sources of contamination, and the amount of pollution entering the ground.

Where a single source of pollution exists and only a small amount of polluting matter enters the ground the contamination does not commonly extend beyond 150 feet. An open well at this distance would probably give no trouble, and a driven well extending 15 feet or more below the water level is almost sure to be safe, providing the rate of movement of the ground water is normal and the pumping not severe.

Where there are several sources of pollution and large amounts of polluting matter are introduced into the ground the contamination may extend in porous materials for some hundreds or even thousands of feet,[a] especially when the underground waters move with considerable velocity. In such places open wells are out of the question, but driven wells carried 20 or 25 feet below the water level will usually afford safe water if not heavily pumped. If the wells are heavily pumped to obtain water for manufacturing purposes or for city supply the water table is usually lowered considerably, the polluted waters likewise sinking to a greater depth. Under such conditions a depth of 50 feet or more below the normal water table is none too much.

[a] Dole, R. B., Use of fluorescein in the study of underground waters: Water-Supply Paper U. S. Geol. Survey No. 160, 1906, p. 81.

COMPOSITION OF MINERAL SPRINGS IN MAINE.

By Frederick G. Clapp.

INTRODUCTION.

Many analyses of mineral-spring waters from Maine and other States have been published from time to time, but no effort has been made to give a summary of the chemical characteristics of spring water in any particular area. Field work done in an investigation of the underground waters of Maine in 1906 and subsequent office work, in which practically all the chemical analyses made of waters in that State were compiled, has enabled the writer to get together much material showing the character of the spring waters, and a summary of the work done is here presented. In the detailed report on this investigation[a] the numerous springs are described and information concerning the character of the water and the volume of the flow, and other facts of interest are presented. For that reason only a brief summary of the composition of the waters will be given here.

SPRINGS OF MAINE.

Number and importance.—Springs are abundant in Maine, especially in the interior of the State. Many of them are situated on hillsides, from which the water can be distributed by gravity to residences and farms. In places several families have combined to have the water of the larger springs distributed through their dwellings by pipes. Here and there the water is raised by windmills.

The water is very cool, temperatures as low as 45° being common, and temperatures over 50° rarely being reported. This low temperature makes the spring waters valuable for use in dairies and creameries.

In those parts of the State where the well water is hard, springs are more generally utilized than where it is soft. In a few places, where the quality of water in the neighboring streams is poor, springs supply manufacturing establishments.

The earliest published work on the mineral springs of Maine was the report by Goodale, issued in 1861.[b] The data contained in this

[a] Clapp, F. G., Underground waters of southern Maine: Water Supply Paper U. S. Geol. Survey No. 223, 1908.

[b] Goodale, G. L., Report on the mineral waters of Maine: Sixth Ann. Rept. Maine Bureau Agr., 1861.

report, consisting of a few analyses, statistics of temperature, etc., were compiled by Peale [a] in 1886. A few springs were described in 1899 by Crook.[b] Otherwise no information has been published regarding Maine springs except the reports of sales of spring waters given in the Geological Survey's annual reports on the mineral resources of the United States.

Commercial springs.—A group of springs of great economic value to the State comprises those which are designated commercial springs, or those of which the waters are sold by measure. In this group there are two subclasses. The first includes springs that furnish table water to consumers in their vicinity at regular intervals. The second subclass comprises springs the waters of which are bottled and shipped to distant points; springs whose waters are commonly supposed to possess medicinal properties, and certain others whose waters are exceptionally pure.

The springs reporting sales in southern Maine at the time this investigation was made were 44 in number, as follows:

Addison Mineral Spring, Addison, Washington County.
Arctic Spring, Bangor, Penobscot County.
Baker Puritan Spring, Old Orchard, York County.
Bluehill Mineral Spring, Bluehill, Hancock County.
Carrabasset Mineral Spring, Carrabasset, Franklin County.
Chapman's Spring, Brewer, Penobscot County.
Cold Bowling Spring, Steep Falls, Limington, York County.
Crystal Mineral Spring, Auburn, Androscoggin County.
Forest Spring, Litchfield, Kennebec County.
Glenrock Mineral Spring, Greene, Androscoggin County.
Glenwood Spring, St. Albans, Somerset County.
Highland Spring, Holden, Penobscot County.
Highland Mineral Spring, Lewiston, Androscoggin County.
Hillside Spring, Bangor, Penobscot County.
Indian Hermit Mineral Spring, Wells, York County.
Ishka Springs, West Hancock, Hancock County.
Katagudos Spring, Eastbrook, Hancock County.
Keystone Mineral Spring, East Poland, Androscoggin County.
Knowlton's Soda Spring, South Strong, Franklin County.
Mount Desert Spring, Bar Harbor, Hancock County.
Mount Hartford Mineral Spring, Hartford, Oxford County.
Mount Oxford Spring, Sumner, Oxford County.
Mount Zircon Spring, Milton Plantation, Oxford County.
Oak Grove Spring, Brewer, Penobscot County.
Old Yorke Spring, Old Orchard, York County.
Oxford Spring Home, Oxford, Oxford County.
Paradise Spring, Brunswick, Cumberland County.
Pejebscot Spring, Auburn, Androscoggin County.
Pine Spring, Topsham, Sagadahoc County.
Pine Grove Spring, Pittsfield, Somerset County.
Poland Spring, Poland, Androscoggin County.

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[a] Peale, A. C., Mineral waters of the United States: Bull. U. S. Geol. Survey No. 32, 1886, pp. 13–16.
[b] Crook, J. K., Mineral waters of the United States and Canada.

Pownal Spring, New Gloucester, Cumberland County.
Pure Water Spring, Waterville, Kennebec County.
Raymond Spring, North Raymond, Cumberland County.
Rocky Hill Spring, Fairfield, Somerset County.
Sabattus Mineral Spring, Wales, Androscoggin County.
Seal Rock Spring, Saco, York County.
Sparkling Spring, Orrington, Penobscot County.
Switzer Spring, Prospect, Waldo County.
Thorndike Mineral Spring, Thorndike, Waldo County.
Ticonic Spring, Winslow, Kennebec County.
Underwood Spring, Falmouth Foreside, Cumberland County.
Wawa Lithia Spring, Ogunquit, York County.
White Sand Spring, Springvale, York County.

In addition to the springs listed above, the following were reported by Peale,[a] with analyses that were made at various dates between 1861 and 1879. It is not known whether these springs are still in use, but they do not report sales:

American Chalybeate Spring, South Auburn, Androscoggin County.
Auburn Mineral Spring, South Auburn, Androscoggin County.
Boothbay Medicinal Spring, East Boothbay, Lincoln County.
Ebeeme Spring.
Fryeburg Spring, Fryeburg, Oxford County.
Lake Auburn Mineral Spring, North Auburn, Androscoggin County.
Lubec Saline Springs, head of Lubec Bay, Washington County.
North Waterford Springs, northwest of Waterford village, Oxford County.
Poland Silica Springs, South Poland, Androscoggin County.
Rosicrucian Springs, Rosicrucian, Lincoln County.
Samoset Mineral Springs, Nobleboro, Lincoln County.
Scarboro Spring, Scarboro, Cumberland County.
Summit Mineral Spring, Harrison, Cumberland County.
West Bethel Spring, West Bethel station, Oxford County.

Analyses of some of the above were taken by Peale from Goodale's report.

Origin of spring waters.—A common but erroneous belief regarding spring waters is that most of them are derived from a distant source. Several spring owners have told the writer that the water from their springs came from the White Mountains, at least 40 or 50 miles distant. Owners of flowing wells in Islesboro have stated their belief that the water of the wells had its source in mountains on the mainland several miles distant.

In certain regions springs may have such an origin. The waters of many mineral springs in the West come long distances underground. In Maine, however, so far as known, no spring or well obtains its supply at a distance of more than a mile from the place where the water emerges. Most spring waters enter gravel deposits on the surface of a hill and find their way downward along the top of the bed rock or hardpan deposits until they find an easy point of

[a] Op. cit.

emergence on the slope. The waters of a few mineral springs issue from joint cracks or from fissures in rock. These waters may come from a considerable depth, but as their temperature is generally about the normal temperature of the region they probably do not come from a greater depth than 100 feet below the surface.

QUALITY OF WATERS.

CLASSES.

The waters of the mineral springs of Maine are mostly of the classes known as "neutral" and "light alkaline-chalybeate." There are, however, a few strong chalybeate waters and several which might be ranked as saline-chalybeate.

NATURE OF ANALYSES.

Sources.—The analyses given on page 74 may be divided into three classes, according to their sources: First, those made by Prof. F. C. Robinson, some of them for the United States Geological Survey, in connection with underground-water investigations; second, those made by Dr. W. W. Skinner, of the Bureau of Chemistry, United States Department of Agriculture, in cooperative work between that bureau and the United States Geological Survey; third, those made by other persons and collected in field work and through correspondence.

In all 75 analyses of Maine mineral waters have been made by about 25 different chemists. Some of these analyses are very reliable; others are less certain.

Variations.—The compilation of the results showed more or less important discrepancies in a few analyses made by different chemists on the same spring water. For example, the water of the Poland Spring, which has probably been analyzed more times than any other spring water in Maine, was reported by different chemists to contain total solids ranging in amount from 63 to 108 parts per million. Two analyses of Pine Spring, in Topsham, both by reliable chemists, show 13 and 33 parts per million of total solids; and the several constituents are similarly diverse in amount. This variation in the composition of the water is due to differences in the season or year when the samples were taken; to their collection at some abnormal time, as immediately after a storm or during a dry period; to variations in chemical manipulation; or perhaps to the fact that the water has stood in bottles for a considerable time before analysis, a factor which may be of some importance.

Forms.—As the chemists of the country have not agreed on any uniform method of reporting analytical results, the analyses collected from different sources were found to vary greatly in form.

In some the results were stated in parts per million, a method which is now generally recognized as the most scientific. In others they were given in grains per gallon, a form of statement that appeals most to laymen. In some they were reported in parts per 100,000 and in some as parts per 10,000. A few analyses, as those made for the Geological Survey and those made by the Bureau of Chemistry, are stated in ionic form. In the many miscellaneous analyses collected from different sources, however, the various elements are commonly grouped together in the forms in which the analyst has thought them to be combined in nature, and the resulting compounds are reported; this method is now generally recognized as misleading, because no chemist can say definitely in what form a certain group of elements is combined in a water. In order to reduce all the analyses to a standard basis which would permit their direct comparison, they were recomputed, mostly by R. B. Dole, of the United States Geological Survey, into parts per million and into the ionic form, and they are so given in the table (p. 74).

Errors.—The investigations in Maine brought to light the fact that errors appear in many analyses of mineral waters published in circulars issued by the owners and in reports of various kinds. These errors are not usually due to intentional misstatements by the owners, some of them being simply printer's errors, in which the decimal points are transposed and chemical terms misspelled, the result being that the analysis shows a compound entirely different from the one it was intended to report. The analysis of one prominent mineral spring in Maine reports "carbonate of iron," whereas what was meant was carbonate of lime. Another circular received by the writer and submitted to the analyst for verification was found to contain three mistakes in the figures.

A defect in some analyses is the omission of any statement indicating the form in which the figures are reported, whether in "grains per gallon," in "parts per million," or in some other form. Of course such an omission renders an analysis valueless.

RANGE IN COMPOSITION.

Total solids.—A study of the 75 analyses of mineral springs shows that the waters vary widely in composition. The total solids run from 11 to 425 parts per million, the lowest figures being found in the spring at Paris Hill, in Oxford County. The water of Pine Spring, in Topsham, Sagadahoc County, which was analyzed by Robinson, shows only 13 parts per million of total solids. The third spring in Maine in respect to mineral purity is Paradise Spring, in Brunswick, Cumberland County, for which Robinson and Carmichael report 17 and 18 parts per million of total solids, respectively. The springs of the Paris Hill Water Company are believed to issue from bowlder clay; Pine Spring and Paradise Spring, situated only a mile apart, on opposite sides of Androscoggin River, issue from sand and gravel overlying clay.

So far as known, the highest mineral content of the springs in Maine is found in the Samoset Mineral Spring, in Nobleboro, Lincoln County. The total solids found in this spring, as reported by Carmichael, are 425 parts per million.

Silica (SiO_2).—The maximum and minimum amounts of the various constituents are not always found in the same springs as those which show the maximum and minimum amounts of total solids. For instance, although the lowest amount of silica (1.2 parts per million) is found in the spring of the Paris Hill Water Company, which shows the lowest total solids, the amount found in the Samoset Mineral Spring, the highest in total solids, is only 12 parts per million, considerably less than the highest amount of silica found in the State. According to the analyses, the spring highest in silica is the Bluehill Mineral Spring, in Hancock County, where 21 parts per million were found. Next to this come the Pejepscot, Windsor, and Poland springs, situated in Auburn, Lewiston, and Poland, in Androscoggin County, only a few miles apart, in which there are 18 and 19 parts per million of silica. Two of these springs can be seen to issue from gneissic rock, and it is probable that rock lies not far below the surface in the third. The lowest proportions of silica are found in springs that issue from bowlder clay and gravel. An interesting feature is that two fairly high reports of silica, 15 and 15.5 parts per million, were found in a spring in the bottom of a limestone quarry at Rockland, Knox County, and in the Pine Grove Spring, near Bangor, notwithstanding the fact that both these springs issue from calcareous rocks.

Organic and volatile matter.—The organic and volatile matter, as reported by reliable chemists, ranges in the springs of Maine from 2.1 to 28 parts per million. The highest report, strange as it may seem, comes from a spring in the bottom of a limestone quarry at Rockland, Knox County, 70 feet below the surface of the ground. The lowest amount is from the spring of the Paris Hill Water Company. A few analyses report organic and volatile matter as absent, but as the complete analyses that have been made show small amounts of these materials, it is probable that the analyses reporting none are in error.

Iron and aluminum oxides ($Fe_2O_3 + Al_2O_3$).—Iron and aluminum oxides range from a trace, reported in several springs, to 8.9 parts per million in the spring in the quarry at Rockland. A comparatively small number of the analyses report iron and alumina, however. It is not known exactly what is meant by the word "trace," but some reports give it as low as 0.

Iron (Fe).—Where iron has been tested separately from aluminum, it has usually been found to be absent, and where present is as a rule not over 1 part per million. The highest amounts reported are 19 and 20 parts per million, in the Samoset Mineral Spring and the Boothbay Medicinal Spring, but as alumina is not reported in these springs, these figures may include that also. The highest amount of iron reported in an analysis where alumina is reported separately is 3.1 parts, in the Bluehill Mineral Spring, which tastes very strongly of iron.

Calcium (Ca).—The lowest amount of calcium reported in Maine is found in the springs of the Paris Hill Water Company. The largest amount is 42 parts, reported in two springs—the Ticonic Mineral Spring, in Waterville, and the Windsor Mineral Spring, in Lewiston. The rocks in these places are not particularly calcareous, and it is somewhat surprising that the calcium should be so much higher than that in the limestone spring at Rockland, which shows only 29 parts.

Magnesium (Mg).—Magnesium is reported absent in several analyses, but as these were not complete the accuracy of the reports can not be vouched for. The lowest reliable report is 0.05 part, in the spring of the Paris Hill Water Company. The highest magnesium reported is 22 parts per million, in the spring in the limestone quarry at Rockland. It is rather interesting to note that in this spring the magnesium amounts to 80 per cent of the calcium found. In most Maine springs the magnesium is below 3 parts per million.

Sodium (Na).—Sodium ranges from 1 part per million in the Carrabassett Mineral Spring, in Franklin County, and the Mount Zircon Spring, in Oxford County, to 19.6 parts in the spring in the limestone quarry at Rockland.

Potassium (K).—In the Rock Hill Spring, in Fairfield, Samoset County, and the Vienna Sparkling Spring, at Vienna, Kennebec County, the amount of potassium is reported as only 0.4 part. From this figure it ranges to 15 parts in the Boothbay Medicinal Spring, at East Boothbay. The potassium in the Samoset Mineral Spring is not reported. Potassium is generally less in amount than sodium, but the Mount Zircon Mineral Spring contains 9.8 parts of potassium and only 1 part of sodium.

Bicarbonate radicle (HCO_3).—As no waters have been analyzed which are known to contain natural carbonates, it is believed that all the carbonates in underground waters in Maine exist in the bicarbonate form. The amount of bicarbonates ranges from 1.14 parts per million in the Raymond Spring, at North Raymond, Cumberland County, to 157 parts in a spring at Brewer, Penobscot County. The latter determination is not from a laboratory analysis, and for that reason the figures are not absolutely trustworthy. The highest amount found in analyses made by reliable chemists was 73 parts, in the Oak Grove Spring, at Brewer.

Sulphate radicle (SO_4).—In a number of the analyses and assays sulphates are reported to be absent. In complete analyses they are generally reported as present, though in small quantities, and for that reason it is believed that they are probably present in all these waters. They range from less than 1 part per million in several springs to 37 parts in the Samoset Mineral Spring, Nobleboro.

Chlorine (Cl).—As would be expected, the amount of chlorine is dependent to a certain extent on the normal chlorine of the region, the lowest chlorine being found in springs in the interior of the State rather than in those near the coast. It is also dependent, however, on the presence or absence of surface pollution and on the character of the formation from which the water issues. The smallest amount reported from the mineral springs in Maine is 0.8 part per million in the Mount Zircon Mineral Spring, in Oxford County. Another chemist, however, reports the amount in this spring as 1.5 parts per million. Several other springs report less than 1 part per million, and from these small amounts it ranges to 60 parts per million in the Sparkling Spring in Orrington, Penobscot County. In well waters chlorine was frequently found to be much higher, independently of the normal chlorine of the region.

Hardness.—Few mineral springs have been tested for hardness, but according to the data at hand it seems to range from 1 to 26 parts per million. Probably, however, it is much higher than this in the regions of calcareous slates in northeastern Maine.

Other elements.—Few of the rare elements are reported in the Maine mineral springs, but this is possibly due in part to the fact that few have been sought. Aside from those mentioned above, the most common constituent tested for is lithium, which occurs in several springs; but with one exception it has been reported either as a "trace," a "minute trace," or "absent." The exception is the Wawa Lithia Spring, at Ogunquit, York County, in which 3 parts per million of lithium was reported, but this figure has not been verified.

RESULTS OF ANALYSIS.

The waters of over 50 mineral springs in Maine have been analyzed, and figures showing the composition of most of them are given in the detailed report on the underground waters of southern Maine.[a] From these has been compiled the following table, giving the observed maxima and minima of each of the principal substances contained.

From the same paper a number of analyses, representing typical spring waters from each county, have been selected and are pre-

[a] Clapp, F. G., Water-Supply Paper U. S. Geol. Survey No. 223, 1908.

sented in the following table for the purpose of showing the general character and range of composition of the various waters:

Range in composition of Maine spring waters.

[Parts per million.]

	Maximum.	Minimum.
Organic and volatile matter	28	2.1
Chlorine (Cl)	60	.8
Silica (SiO_2)	19	1.2
Oxides of iron and aluminum ($Fe_2O_3+Al_2O_3$)	9	Trace.
Calcium (Ca)	42	1.2
Magnesium (Mg)	22	.05
Sodium (Na)	127	1.0
Potassium (K)	15	.4
Bicarbonate radicle (HCO_3)	157	.14
Sulphate radicle (SO_4)	37	.00

Selected analyses of waters of mineral springs in Maine.

[Including typical waters from each county.]

No.	County.	Locality.	Owner.	Name of spring.	Total solids.
1	Androscoggin	South Poland	Hiram Ricker & Sons	Poland Spring	108.651
2	Cumberland	Brunswick		Paradise Spring	18.0
3	Franklin	Carrabassett	Carrabassett Mineral Spring Co.	Carrabassett Spring	72.0
4	Kennebec	Litchfield	Forest Springs Water Co.	Forest Spring, No. 1	[a]100.0
5	Knox	Rockland		Spring in bottom of limestone quarry.	234.2
6	Lincoln	Nobleboro		Samoset Mineral Spring	425.0
7	Oxford	Milton plantation.	Mount Zircon Spring Co.	Mount Zircon Mineral Spring.	[b] 33.0
8	do	Paris	Paris Hill Water Co	Crocker Hill Spring (public supply).	[a] 11.0
9	Sagadahoc	Topsham	Pine Spring Water Co.	Pine Spring	13.0
10	Washington	Harrington	Quantabacook Water Co.	Harrington (public supply)	70.0
11	York	Old Orchard	Olde Yorke Springs Co.	Olde Yorke Spring	94.0

No.	Organic and volatile matter.	Silica (SiO_2).	Iron and aluminum oxides. ($Fe_2O_3+Al_2O_3$).	Iron (Fe).	Calcium (Ca).	Magnesium (Mg).	Sodium (Na).	Potassium (K).	Bicarbonate radicle (HCO_3).	Sulphate radicle (SO_4).	Chlorine (Cl).	Carbonate radicle (CO_3).	Material.	Analyst.
1	......	15.40	......	......	14.37	2.38	6.34	0.90	55.63	3.29	5.90	......	Granite.	W. W. Skinner.[c]
2	0.34	6.6	......	0.09	.68	.28	2.8		......	1.0	1.6	4.2	Gravel	F. C. Robinson.
3	......	14.0	5.3	......	8.2	4.3	2.8	1.6	......	16.0	4.4	15.0	...do..	Salvatore La Bua.
4	3.0	14.0	......	Tr.	22.0	1.6	5.3	2.7	......	9.0	3.0	38.0	...do...	F. C. Robinson.
5	28.2	15.0	8.9	......	28.8	22.4	19.6	4.7	......	29.1	6.1	......	Limestone.	Do.
6	Tr.	12.0	......	19.0	23.0	1.9	127.0	......	......	37.0	11.0	192.0	......	H. C. Carmichael.
7	2.2	9.7	......	.66	2.3	......	1.0	9.8	......	5.4	1.5	......	Till...	F. L. Bartlett.
8	3.7	1.2	.33	......	.51	.05	1.8		......	......	3.9	......	...do...	
9	......	4.6	......	.33	1.0	.03	2.0		......	.2	2.3	3.1	Gravel	F. C. Robinson.
10	11.9	13.1	1.2	......	16.6	1.8	6.0	1.1	......	6.5	9.0	......	...do...	Do.
11	......	4.2	......	.06	14.0	3.5	11.0	5.8	......	8.2	12.0	34.0	......	Do.

[a] Including lithium, trace.

[b] Including aluminum, trace.

[c] Analysis made in cooperative work between United States Geological Survey and Bureau of Chemistry. The following substances were also found: PO_4, trace; BO_2, none; NO_3, 3.98; NO_2, none; bromine, none; iodine, none; Fe and Al, 0.32; Mn, none; Li, none; NH_4, 0.011; oxygen to form Fe_2O_3 and Al_2O_3, 0.130.

SALINE ARTESIAN WATERS OF THE ATLANTIC COASTAL PLAIN.

By Samuel Sanford.

INTRODUCTION.

Extent.—The land area of the Atlantic Coastal Plain stretches from New York Harbor to the Florida straits. East of New York, except for patches, such as Long Island, Block Island, and the islands of Buzzards Bay and of the east coast of Massachusetts, the coastal plain is almost completely covered by water, its underwater extension reaching to the edge of the Banks of Newfoundland, nearly a thousand miles beyond Boston. This paper treats of underground waters in a strip of the plain extending from New York to Florida, about 800 miles in an air line, with a width gradually increasing from 20 miles at Sandy Hook to 63 miles at Cape May, 72 miles at Cape Charles, 175 miles at Cape Hatteras, and 135 miles at Charleston.

Geology.—The Coastal Plain is underlain by a great succession of sedimentary deposits, mostly unconsolidated, consisting of gravels, sands, clays, marls, and loams. In places the sands and clays are indurated enough to form sandstones and shales. In places also the marl beds are so full of shells and calcareous débris that they form lime rocks. No solid limestones (limy beds compact enough to be used as building stone) occur north of the Virginia-North Carolina line, but south of it, in North Carolina, South Carolina, and Georgia, some of wide extent are found. All the members of the great succession of deposits have a general east or southeast dip, the inclination being measured in feet per mile rather than in degrees, and all overlie a floor of crystalline rock that dips seaward at a slightly greater angle. This floor was once a peneplain, a rock surface reduced by the action of streams through thousands of years to an almost uniform slope. A general subsidence carried it below the level of the ocean and the Coastal Plain sediments were gradually deposited upon it. This peneplain, however, was not perfectly flat, but had within distances of a few miles differences of elevation of 100 or 200 feet, many of which were not obliterated by the advancing sea. Neither was the sedimentation continuous. At times the land rose, the sea retreated, and the sediments that had accumulated were eroded. In the course of alternate depressions and elevations of the land the bed rock was gently bowed or warped, so that some places were more deeply eroded in retreats of the sea and more thickly covered in advances than others. Because they lie on such a lumpy, irregularly warped floor the total thickness of the deposits at points equally distant from the western margin varies decidedly.

Few wells near the coast have been sunk to this crystalline floor, but the deep drilling that has been done indicates that the Coastal Plain sediments at Atlantic City, N. J., are probably 3,000 feet thick; at Ocean City, Md., and near Franklin City, Va., possibly 3,500 feet; and at Charleston, S. C., perhaps 2,500 feet. At Fort Monroe, Va., the total thickness is known to be 2,250 feet and at Fort Caswell, N. C., 1,540 feet.

ARTESIAN WATERS.

Occurrence.—As the deposits of the Coastal Plain are largely unconsolidated and include many sandy beds outcropping in a region of copious rainfall and having a general seaward dip, they contain great stores of artesian water, which are, possibly, the most valuable underground resource of the area under consideration. This resource has been extensively developed in the last twenty years and hundreds of wells are sunk annually. Though all the water-bearing beds have not been found, enough work has been done in New Jersey to demonstrate the existence in that State of potable water at fully twelve horizons of wide extent. At least six water-bearing sands occur in Maryland and Virginia, and there are probably as many in North Carolina, South Carolina, and Georgia.

Quality.—In Virginia and the States to the north the beds yield water that is prevailingly soft—that is, water that contains only small amounts of lime and magnesia. In North Carolina and South Carolina, though soft waters probably predominate in deep-lying beds, hard waters are of wide occurrence, particularly at depths of less than 300 feet. Whether hard or soft, however, the true artesian waters, those which rise notably in the well when a water bed is pierced, are as a rule derived from sources that are beyond the possibility of contamination by surface impurities, and, being germ free, they are usually better for drinking than the easily polluted supplies obtained from dug wells. They have been used chiefly for domestic purposes at individual dwellings, but also for public-supply systems and by railroad companies and many manufacturing concerns.

Development.—Most of the wells drilled are of small diameter, 1 inch to 2 inches, and cost from $10 to $100, but many of larger diameter, costing from $500 to over $5,000, have been put down, and the number of these is increasing. It is safe to say that fully 10,000 artesian wells costing from $10 to $38,000 have been sunk in the Coastal Plain, and that the total investment in such wells exceeds $1,000,000.

SALINE WATERS.

GENERAL STATEMENT.

Though most of the Coastal Plain flows are adapted for household use and some make excellent boiler water, at a number of places flows have been tapped, mostly at depths of several hundred feet, which are called brackish or salt. Most of these are poor boiler waters and some are not suited for drinking, except for their medicinal value. Owing to a widely held opinion that where salt water has been struck fresh water can be obtained by sinking to some particular underlying formation, or by drilling deep enough, an attempt is made in this paper to summarize the essential data collected by the Geological Survey on the occurrence of saline flows and the position and extent of beds yielding salt water.

Many thousands of dollars have been spent in fruitless exploration for fresh water in salty areas, one deep well at Fort Monroe having cost the Government nearly $35,000; and the growing interest in artesian supplies and the rapid increase in the number of wells indicates that much time and money may be wasted in similar attempts in the immediate future. Hence it is desirable that well drillers and persons contemplating drilling should be informed of doubtful localities and the probabilities in such places.

DEFINITION OF SALT WATER.

The question what is a salt water can be variously answered, but here it is assumed to be a water having a salt or brackish taste. Estimates of the amount of common salt (sodium chloride) that in solution will give such a taste vary widely, different chemists stating the proportion at 500 to 1,200 parts per million of water. A factor of importance in natural waters is the effect of other substances in solution. A water high in sodium chloride but containing much sodium bicarbonate (a substance that is present in large amount in many deep flows in the Coastal Plain), is much pleasanter to the taste than a water which contains an equal amount of sodium chloride, but in which the sodium bicarbonate is replaced by calcium bicarbonate, the predominating mineral substance in many shallow flows. The standard, therefore, must be more or less arbitrary. The accompanying table includes data from (1) all localities where artesian water has been called salt and where no analyses have been made, and (2) all places where analysis has shown the waters to contain more than 800 parts per million of sodium chloride (equivalent to 500 parts of chlorine). The summarized data relate to one or more wells in every area where salt water has been reported at a depth of more than 100 feet. Wells less than 100 feet deep are not included, because shallow brackish waters resulting from the direct entrance of sea water to the beds do not have any necessary relation to the deeper waters under consideration.

Saline wells in the Atlantic Coastal Plain.

Locality.	Date.	Depth (feet).	Depth main salt-water horizon (feet).	Yield (gallons per minute).	Salinity (parts per million of chlorine).	Age of saline beds.	Waters above main salt-water horizon.	Waters below main salt-water horizon.	Remarks.
NEW JERSEY.									
Cape May County:									
Cape May Point.	1879	224	224	....	Salt.....	Miocene...............	....	....	Abandoned; other wells get good water at 320-360 feet.
Wildwood......	1900	326	10 to 260	Strong flow.	...do.....	Quaternary; Miocene (?).	Fresh water at 75 and 101-106 feet; salt water at 215 feet.	Fresh water at 290 and 326 feet.	Water from 290 feet used.
Do.........	1894	1,244	1,185	...do...	...do.....	Eocene...............	Fresh water at 75, 625, 845, and 930 feet.	....	Fresh water from 930 feet used.
DELAWARE.									
Sussex County:									
Lewes	1898	1,080	1,080	38.....	Very salt	Pamunkey...........	Salt water at 891 and 950 feet; fresh water at 400, 625, and 750 feet.	....	Abandoned.
MARYLAND.									
Anne Arundel County:									
Thompsons Point.	1908	300	150	....	... .	Potomac...............	Fresh water at 25-100 feet	....	Water below 100 feet too salt for use.
Worcester County:									
Pocomoke......	1900	496	225	....	Salty....	Chesapeake...........	Good water at 75-85 feet; hard water at 120 feet.	Salty water at 290 feet; salt sulphur water at 485 and 495 feet.	Water used from 195-225 and 247-290 feet.
Do.........	1907	1,500	480	*a* 25...	1,180....	.....do...............	.....do.....................	Fresher water at 1,200 feet and below.	Water from 1,200 feet and below used occasionally.
VIRGINIA.									
Accomac County:									
Onancock......	1894	480	140	Small.	Brackish	Chesapeake	Fresh water at 16, 30, and 50 feet.	No water below 140 feet.....	Abandoned.
Tangier Island.	1904	250	140	...do...	...do.....	.....do. (?)...........	Fresh water at 85 feet.........	.....do.....................	Water from 85 feet used.
Elizabeth County:									
Fort Monroe...	1902	2,250	1,320	....	Very salt	Potomac...............	Salt water at 285, 630, and 980 feet.	Very salt water at 2,131 feet.	Never used.
Hotel Chamberlin.	1896	945	945	25.....	*b* 4,978...	.....do...............	....	....	Used for flushing.
Gloucester County:									
Achilles........	1902	610	610	*a* 1.....	*b* 1,400...	Pamunkey............	Water at 450 feet............	....	Domestic use.

Do.	1904	570	570	[a] 1/2	[b] 1,570	do	do		Do.
Roanes	1898	716	716	[a] 52	[b] 1,630	Marine Cretaceous	Water at several horizons		Used for washing.
Do	1894	850	850	[a] 1/3	[b] 1,100	Potomac			
Severn	1902	610	575	[a] 1/8	[b] 2,500	Pamunkey	Fresh water at 8, 24 feet; water at 504 feet.	Water at 610 feet	Little used.
Mathews County:									
Fitchetts	1904	110	110			Chesapeake	Slightly brackish water at 50 feet.		Water from 50 feet used in boiler.
Norfolk County:									
Lambert Point.	1890	616	610	[a] 65	[b] 292	Marine Cretaceous			Used for drinking and washing.
Northampton County:									
Bone Island		169	169		610	Chesapeake (?)			Domestic use.
Cherrystone Island.	1899	240	240(?)	[a] 10–80		do			Boiler supply.
Princess Anne County:									
Moores Bridges.	1898	1,760	1,072	[a] 150	[b] 1,700	Potomac	Salt water at 738, 783, 805, 950, 975, 984, and 1,038 feet.	Salt water at 1,190, 1,220, 1,227, 1,480, and 1,760 feet.	Well dynamited; present flow salt sulphur water from unknown depth.
NORTH CAROLINA.									
Beaufort County:									
Washington		360+	360+		Salt (?).	Marine Cretaceous			Abandoned.
Brunswick County:									
Quarantine Station.	1896	400	400	[a] 8,800–235.		do			
Wilmington	1899	1,330	1,019	[a] 7,400.		do	Hard fresh water at 1,000 feet; brackish water at 379, 496, 518, 574, and 990 feet.		Lowest chlorine after pumping one hour.
Columbus County:									
Cronly		278	278(?)	[a] 747					Little used.
Craven County:									
Newbern		353	300	100	Very salt	Marine Cretaceous			Not used.
Hyde County:									
Fairfield			220–280		[b] 2,860	Miocene	Fresh water at 80 feet		Abandoned.
Swanquarter			260+			do			Do.
New Hanover County:									
Castle Hayne	1906	370	340	Large flow.	Very salt	Marine Cretaceous	Hard, fresh water at 10 and 93 feet; salt water at 270 and 338 feet.		Do.
Fort Caswell	1907	1,542	1,440		10,400	do. (?)	Water at 100 feet		Not used.
Do	1902	836	836	2	[b] 7,840	do	Salt water at 365, 719, and 800 feet.		Do.

[a] Flow at surface.

[b] Analyzed in 1906.

Saline wells in the Atlantic Coastal Plain—Continued.

Locality.	Date.	Depth (feet).	Depth main salt-water horizon (feet).	Yield (gallons per minute).	Salinity (parts per million of chlorine).	Age of saline beds.	Waters above main salt-water horizon.	Waters below main salt-water horizon.	Remarks.
NORTH CAROLINA—continued.									
Pasquotank County:									
Canaan	1903	615	300	Very salt.	Very salt	Miocene	Hard water at 14, 36, 60, and 260 feet.	Salt water below 300 feet	Abandoned.
Elizabeth City		300+	300+			do	Hard water at 250–300 feet	Salt water somewhere below 300 feet.	Do.
Tyrrell County:									
Columbia			348		Salt (?)	do			Do.
SOUTH CAROLINA.									
Beaufort County:									
Beaufort			500(?)			Eocene (?)			
Folly Island			500(?)			do			
Port Royal Island.			500(?)			do			
St. Helena Island.			500(?)			do			
Charleston County:									
Charleston	[a]1868	1,260	1,250		715	Marine Cretaceous			
Do	[a]1879	1,970	1,950		121	do	Water at 960, 1,000, 1,557, 1,590, 1,862, and 1,880 feet.		Domestic use.
Do	[a]1880	425	425(?)		1,486	do			
Do	[a]1877	380	380		[b]2,300	Eocene (?)			

[a] Date of analysis. [b] Estimated.

SALT-WATER AREAS.

As the table shows, no deep salt waters have been recorded in the Coastal Plain in New Jersey, except at Cape May Point and Wildwood, in the extreme southern part of the State. There is no mention of salt water in the log of the 2,306-foot well at Atlantic City, although, except for the 2,350-foot well at Key West, Fla., that well is the deepest in the entire Atlantic Coastal Plain. Salt water has been reported at Lewes, Del.; Pocomoke, Md.; in Accomac and Northampton counties, on the eastern shore of Virginia; and in Mathews, Gloucester, Elizabeth City, Norfolk, and Princess Anne counties, on the western shore. In North Carolina salt water is known to have been found by deep wells in Hyde, New Hanover, Columbus, and Brunswick counties, and was presumably found in Pasquotank, Tyrrell, Beaufort, and Craven counties. In South Carolina it was found in Beaufort and Charleston counties. In Georgia, though it is altogether likely that salt water has been struck, the wells have not been reported.

RELATIONS OF SALT-WATER BEDS.

It is noteworthy that except in North Carolina all the salt-water areas are near the sea or in low land bordering the seacoast. The North Carolina wells are in a stretch of country that is nowhere 50 feet above tide; much of it has an elevation of less than 20 feet. The salt-water wells of Virginia, Maryland, Delaware, and New Jersey are in areas having elevations of less than 25 feet.

Although at probably all the wells some fresh water was found above the salt, at but four localities—Wildwood, N. J., Pocomoke, Md., Chisholm Island, S. C., and Charleston, S. C.—has fresher or decidedly less saline water been found below salt; at Crisfield, Md., waters containing but 136 parts of chlorine per million lie 770 feet below waters containing 291 parts, but neither of these is a "salt" water according to the definition on page 77. At one locality, Wildwood, N. J., flows of fresh and salt water were found to alternate to a depth of nearly 1,200 feet, but at five localities where wells have been sunk with care and different flows tested—Lewes, Del., Fort Monroe and Norfolk (Moores Bridges), Va., and Wilmington and Fort Caswell, N.C.—no fresh water has been found with increase in depth, though at the well in Hilton Park, Wilmington, the flow at 1,020 feet is a little less salty than the one above. From the Elizabeth City County wells it is safe to assume that the deep wells in eastern Gloucester County, Va., would not find fresh water at greater depth.

A comparison of the data in the table shows that salinity bears no apparent relation to the depth of beds below surface or to their age, and it is doubtful if the saline areas bear any relation to the very slight folds that exist in the Coastal Plain. Not one of the areas is like those reported from Alabama, where natural gas in associated with the flows. At some of the Atlantic Coastal Plain areas enough sulphureted hydrogen is given off to cause a decided "sulphur" odor, but at others no such odor is perceptible. The Coastal Plain wells have but one feature in common—location near a large body of salt water or in low land.

CAUSES OF SALINITY.

Sea water.—The first suggestion that occurs to anyone seeking a reason for salt flows is that the beds yielding them were marine deposits and that the sea water imprisoned within the sediments has never been replaced by fresh water. One objection to this view is that though most of the flows cited in the table come from marine beds, the Potomac group, presumably of fresh-water origin, yielded salt water at Fort Monroe throughout a section of over 800 feet. Another objection is that the salt artesian waters do not resemble sea water in composition, as the following analyses show:

Analyses of sea water and water from salt wells.

[Parts per million.]

	Sea water.[a]	Severn, Va.[b]	Fort Caswell, N. C.[c]	Charleston, S. C.[d]
Total solids	35,000	5,008	17,634	3,679
Silica (SiO_2)	....	39	5.6	45
Iron (Fe)	....	4.9	8.4	....
Calcium (Ca)	419	46	598	21
Magnesium (Mg)	1,304	26	40	33
Sodium (Na)	10,707	1,826 (Na + K)	6,440	1,157
Potassium (K)	387		9	71
Carbonate radicle (CO_3)	72	0	0	299
Bicarbonate radicle (HCO_3)	....	628	868	....
Sulphate radicle (SO_4)	2,693	216	26	175
Chlorine	19,352	2,500	10,400	1,489

[a] Dittmar.
[b] R. B. Dole, analyst.
[c] J. R. Evans, analyst.
[d] Shepard Laboratory, analyst.

Too much weight may be given to the differences shown above between sea water and the water of the salt wells if the possibility of chemical reactions which might result in the precipitation of lime and magnesium salts from the buried sea water is disregarded, but at least they indicate that the present flows are not unchanged sea water. In fact, it would be strange if they were. Successive elevations and depressions of the land are recorded in the geology of the Coastal Plain. In periods of elevation underground circulation has been quickened and fresh water has gradually leached marine deposits and forced out any original sea water. In periods of depression the outcrops of fresh-water bearing beds have been saturated by sea water and blanketed by marine deposits. Another period of elevation has started fresh water down the dip, displacing sea water, leaching marine deposits, and forcing the salt but freshening solutions into the underlying beds. Thus, a bed that originally was a fresh-water deposit may have been repeatedly invaded by salt water from above and the present salinity of the water in a particular area is to be regarded as connected with the last invasion of salt water rather than with any sea water imprisoned in the beds at the time of deposition.

Slow circulation.—Differences in mineralization due to differences in the origin or the composition of a particular bed, or of underlying beds, may be modified by differences in the ease of circulation of water through them. As the members of the Coastal Plain formations tend to lenticular form and varied texture, water that enters an artesian bed does not progress seaward along a straight line down the dip, but may cut across beds through joint cracks, rising or sinking on the way, may follow a zigzag course through connecting lenses of sand, and conceivably may flow up the dip for short stretches. As the inclination of most of the formations is slight, and as most of the waters do not run through open channels for any great distance but more through capillary spaces between grains of sand, their passage is slow and they constantly lose head. In their journey they dissolve various mineral substances, the work of solution at any particular point being determined by temperature, pressure, and substances already in solution. An increase in the proportion of clay in a certain sand bed may check the seaward movement, or the bed may pinch out altogether, ponding the water landward. This ponded water, already more or less mineralized, may dissolve the minerals of the bed in which it lies and thus become more mineralized than water at an equal distance from the outcrop but having a freer passage toward the sea. On the other hand, the fineness of a bed at the precise spot at which it is tapped by a well is not necessarily significant, for the outlet from coarse beds may be obstructed as readily as that from fine beds. Some of the most saline flows in Virginia come from gravels or coarse sands.

To recapitulate, the salinity of a flow may be derived from sea water or from water that has leached marine deposits and sunk down the dip, following an elevation of the land. The location of salt-water areas is determined by original or imposed salinity and subsequent imperfect circulation. Salt-water beds freshen as circulation down the dip is established; they are found near the coast chiefly because the percolating meteoric waters have not been able to complete their work farther since the last invasion of the sea. However, wells less than 200 feet deep, situated on islands or on the shores of a wide body of salt water, may be subject to a slight but effective seepage of sea water through the beds overlying the sand, particularly if they are heavily pumped.

In comparing places miles apart account must be taken of differences in initial head caused by differing elevation of the outcrops of the porous beds.

LATERAL CHANGE IN SALINITY.

Freshening of areas.—Owing to the tendency to lenticular form and the varying texture of the beds of the Coastal Plain, it is sometimes impossible to trace a particular water horizon more than a few miles or to determine the exact correspondence of a salt-water bed with a bed some miles distant yielding fresh water. The measure of freshening from a salt-water area in a series of beds can, however, be determined. At some places there is notable variation in saltness within a few miles. At others the change is more gradual. At Charleston, S. C., as shown by C. W. Shepard, jr.,[a] the salt-water area is rather sharply defined landward. The water from a 425-foot well at Chisholm's Mill, three-fourths of a mile from the city hall, contained 1,489 parts of chlorine per million and that from a 375-foot well of the Edisto Phosphate Company, 4 miles away, contained only 849 parts.

A similar instance of westward freshening is furnished by wells near Norfolk, Va. A bed at 738 feet in the Norfolk waterworks well yielded water containing 1,165 parts of chlorine per million; the 616-foot Norfolk and Western Railway well at Lambert Point, 6 miles farther west, yielded water containing only 351 parts. In Gloucester County, Va., the flow of a 594-foot well at Gloucester Point contains 300 parts per million of chlorine; the flow of a 610-foot well 4½ miles to the northeast contains 1,400 parts, and that of a 585-foot well 6½ miles to the northeast contains 2,500 parts. At Wilmington, N. C., the deep well at Hilton Park flows, presumably from a depth of 1,020 feet, water containing 7,400 parts of chlorine per million; and the deep well at Fort Caswell at the mouth of Cape Fear River, 25 miles farther south, flows from a depth of 1,440 feet water carrying 10,400 parts. All the above comparisons are weakened by the differences between the time of drilling and that of making analyses—that is, they take no account of possible freshening through flowing.

Freshening of individual wells.—The quickening of circulation that follows the tapping of a water bed by a well must ultimately result in freshening a salt flow. Fuller,[b] who suggests that such salt wells be allowed to flow freely in the hope of their finally yielding fresh water, mentions instances of improvement near Wilmington, two permanent and two temporary. The temporarily bettered wells

[a] Artesian wells, Municipal report of the city of Charleston, 1881.

[b] Fuller, M. L., Instances of the improvement of water in wells: Water-Supply Paper U. S. Geol. Survey No. 160, 1906, p. 96.

became fresh after heavy pumping for half an hour to an hour, and become salty again when disused. They seem to be in a distinct class, and their peculiar behavior may perhaps be accounted for by imperfect casing and by the drill having struck two flows, one fresh and the other salt.

No analyses of the permanently improved flows were made just after the completion of the wells, so the exact amount and rate of freshening can not be determined. Analyses are the only safe guides in comparison, taste being too uncertain, and analyses of Coastal Plain flows for a term of years are few. They are available, however, for the Norfolk and Western Railway well at Lambert Point and the 1,250-foot well on Wentworth street, Charleston.

In the Lambert Point well the water contains less than 500 parts of chlorine per million and is therefore not a salt water, as previously defined. The analyses are as follows:

Analyses of water from well of Norfolk and Western Railway, Lambert Point, Va.

[Parts per million.]

	1.	2.	3.	4.
Total solids	1,093	1,094	....	1,128
Silica (SiO_2)	10.0	11.4	11.0	6.0
Oxides of iron and aluminum ($Fe_2O_3+Al_2O_3$)	.91	1.37	2.6	1.9
Calcium (Ca)	5.0	5.4	4.8	5.1
Magnesium (Mg)	1.7	2.8	2.7	3.3
Sodium (Na)	415.0	439.0	434.0	437.0
Potassium (K)	21.0			
Sulphate radicle (SO_4)	43.0	44.0	43.0	45.0
Carbonate radicle (CO_3)	245.0	314.0	....	312.0
Bicarbonate radicle (HCO_3)	....	....	617.0	....
Chlorine (Cl)	351.0	290.0	293.0	290.0

1. Shepard Laboratory, analyst, 1891.
2. Norfolk and Western Railway Company, analyst, 1899.
3. Dearborn Drug and Chemical Company, analyst, 1907.
4. Norfolk and Western Railway Company, analyst, 1909.

Allowance being made for differences in analytical methods, the rate of freshening shown is indefinite and is so slight that it would not pay to sink a well near by in the hope of ultimately getting fresh water from it.

Comparisons can be made of the Charleston waters in but one well, the 1,250-foot well on Wentworth street. An average of analyses made in 1868 shows 776 parts of chlorine per million. A field test made in 1907 showed over 900 parts. If there is no break in the casing, the salinity has increased.

SUMMARY.

Areas in which salt water may be found by deep drilling are more numerous than has been supposed.

These areas are in low ground and the greater part are near the ocean or some large body of salt water.

There is no foundation for the opinion that fresh water can always be found below salt or can be found in a particular formation where salt water has been found in an overlying formation. The probability of finding fresh water below salt is a problem for each area, and inferences based on work in one area may be utterly misleading in another.

As salt-water beds freshen up the dip and as the seaward limits of most of them are unknown, the prospect of finding fresh water is better to the west rather than to the east of any particular salt-water well.

Salt flows are not peculiar to any one horizon and have no known relation to the geologic age of a deposit.

Salt flows are due to various causes; chiefly (1) to the leaching of marine deposits and (2) to the penetration of sea water or the leaching of marine beds into underlying deposits. Differences in rate of circulation caused by differences in initial heads, loss of porosity, or pinching out of water-bearing beds will account for some differences in mineralization.

Although a renewal of active circulation through a well must result ultimately in freshening the flow, so little is known of the rate of freshening that drilling wells in a salt area in the hope of getting fresh water is not advisable unless rapid freshening in a particular locality has been proved.

MAGNETIC WELLS.

By Myron L. Fuller.

INTRODUCTION.

It is a fact well known to deep-well drillers that the casings of many deep borings are more or less magnetic and will attract and hold to the pipe small iron or steel objects coming within their sphere of influence. Furthermore, many newspapers and occasionally engineering and other magazines have printed statements ascribing magnetic properties to the water itself, and it is not unusual for spring waters to be exploited as "magnetic." A large number of these waters were investigated, and in most of them no magnetism whatever was found; in others the only magnetism was that shown by the well casings. The object of the present paper is to put on record some observations on magnetic wells and so-called magnetic spring waters, and to suggest certain lines of experiment which will afford more reliable data as to the phenomena observed.

PHENOMENA.

MAGNETISM OF CASINGS.

Occurrence.—During or after the drilling of wells it is frequently found that the casing has become magnetized. This discovery is usually made through the adherence to the pipe of nails or other small objects brought near it. The phenomenon is exhibited principally in the attraction of small objects to the pipe, the clinging of steel tapes and wires to the casing when measuring the depth of wells, the attraction of steel cables to the casing in drilling, and the attraction of the magnetic needle when in the vicinity of the casing.

As a rule, the magnetism of the casing is only sufficient to hold small nails or similar objects, but occasionally it is much stronger, and will hold nuts, bolts, and spikes against the pipe, and it is reported that even metal dippers and other large objects have been likewise held. The casing of a well at Wheeling, W. Va., tested by Prof. William Hallock for the United States Geological Survey, was 4,500 feet in length and is said to have had sufficient magnetism to hold a wrench.

In the measurement of certain wells the magnetism of the casing presents an important obstacle. A. C. Lane has found that the cling of the steel line used in lowering thermometers into deep wells is very considerable. He says[a] that in the well at Grayling, Mich., it required a man's full strength to start 2,600 feet of steel tape, although the weight of the tape itself was not over 25 pounds. Again, he reports that in a well at Cheboygan the magnetic drag on the tape used in measuring was so great, according to Mr. Rust, the driller, that it was impossible to tell when the 20-pound weight had reached the bottom.

As would naturally be expected, the needle of a compass is strongly attracted by a magnetic casing, being deflected toward the well in all positions for distances varying with the strength of the magnetism.

Relation to depth of well.—The relation between the length of the casing and the strength of the magnetism is not constant. According to Lane,[b] however, the larger and deeper holes are in general more magnetic than the shallower ones. This would probably always be true if all other conditions were uniform, which is generally not the case. In reality the magnetism of the casings in many of the deeper wells is feeble, whereas in some shallow wells, as in the 90-foot drift well of the Moline Plow Company at Madison, Wis., examined by A. R. Schultz, of the Geological Survey, the magnetic force was sufficient to hold a hammer and a heavy wrench against the pipe.

Relation to location.—The data bearing on the distribution of magnetic wells are too few to permit other than broad generalizations. Only one such well has come to the attention of the writer in the coastal plain regions of the Atlantic or Gulf States, and only a few have been reported from the Central States. In Pennsylvania, however, the drillers report that magnetic casings are common, the development occasionally being rather strong. Magnetic wells are especially numerous in Michigan, Wisconsin, and Minnesota. About a dozen came to the attention of Mr. Schultz in a season's investigation in Wisconsin, and it is probable that there are hundreds of others in which the magnetism exists but has not been noticed.

Relation to materials penetrated.—Information regarding the relation of the magnetism of casings to the materials in which the well is drilled is very fragmentary. Wells in Carboniferous sandstones, shales, and limestones and in Upper Devonian shales are magnetic in Pennsylvania, Michigan, and elsewhere, and wells in drift are not uncommonly magnetic in the north-central States. No reliable reports of magnetic wells in granite have been received, but it is believed that they would be as common or even more common than those in the rocks just mentioned were it not that their casing is carried only a few feet into the rock. One magnetic well is known in the Coastal Plain, and there is no reason why others should not be found. For the reasons outlined in the paragraphs on the causes of

[a] Fourth Report Michigan Acad. Sci., 1904, pp. 166-167.

[b] Loc. cit.

the phenomena, magnetic wells are most numerous and powerful in the harder rocks, in which the casings are carried to the bottom, and least common in soft, unconsolidated deposits. Wells in drift or other deposits carrying magnetic sands or bowlders, however, would be exceptions to this rule. Theoretically the magnetism should be greatest in wells in granites and quartzites, and should decrease more or less progressively through schists and other soft crystalline rocks, limestones, sandstones, slates, shales, clays, etc.

Loss of magnetism.—The testimony of drillers seems to be unanimous that the magnetism decreases with the lapse of time and in many wells disappears in a few years. One of the best examples is afforded by a well sunk near Grand Valley, Pa., in 1905. At that time it was found by the driller, Josiah G. Winger, to be strongly magnetic. On repeating the test a few months later, at the Survey's request, he found that the magnetism had entirely disappeared. A considerable number of so-called magnetic wells have been tested by the writer and other members of the Survey, but the magnetism was not detected, apparently having disappeared since the completion of the wells.

MAGNETISM OF DRILLS.

Magnetism of the drill is less commonly reported than magnetism of the casings, although well drillers in the Pennsylvania oil and gas fields say that it is very common. Mr. Schultz found that in the well of the Moline Plow Company at Madison, Wis., the drill, though strongly magnetic, was much less so than the casing, which held a hammer and iron wrench, the largest objects held by the drill being nails. It will probably be found on testing that magnetic drills are very common, but that the magnetism is as a rule not so strongly developed as in casings.

MAGNETISM OF WATER.

In the course of his field work the writer has visited a number of wells whose water is alleged to produce magnetism in iron objects immersed in them, and waters from several "magnetic" springs (in reality deep wells) are on the market. So persistent have been the reports of such waters that, notwithstanding their apparent inherent improbability, the writer has taken every occasion to make careful tests in the field.

The waters of most of the so-called magnetic springs emerge from pipes, and are thus artesian wells rather than true springs. In these, as well as in natural springs, the waters are generally strongly chalybeate and deposit considerable amounts of iron oxide, which doubtless suggested the tests for magnetism. The phenomena reported consist in the magnetization of needles, knife blades, nails, etc., immersed in the water, both at the source and at a distance, and in the deflection of the magnetic needle in its vicinity.

To test the matter, two members of the United States Geological Survey visited one of these springs (the Cartersburg Spring (well) near Indianapolis, Ind.) at different times and carefully tested the steel (1) before approaching the "spring," (2) immediately before placing the knife in the water held in the glass jar, and (3) after allowing the knife to stand in water for five minutes at various distances from 5 to 150 feet from "spring." No magnetism whatever was produced by the water and even the casing was found to be nonmagnetic.

The waters of this "spring" or well are strongly chalybeate and, according to J. N. Hurty, chemist for the Big Four Railroad, deposit magnetic oxide of iron.

Similar tests made by the writer and others on alleged magnetic wells in Ohio and Minnesota gave the same negative results.

Objects were reported to have been magnetized by the water in the Moline well at Madison, Wis., but investigation brought out the fact that the water had been collected in a metallic dipper which possibly came into contact with the magnetized casing and was magnetized by it, and which in turn magnetized the iron placed in it. Tests by Mr. Schultz showed that unmagnetized steel or iron left for an hour in the water in nonmagnetic vessels showed no magnetic properties, nor did iron held in the water in the well when carefully shielded from the casing. J. G. Winger made a careful test of the well near Grand Valley, Pa., and found that although the casing was strongly magnetic the water showed no magnetic phenomena. In fact, there is at present no evidence that magnetism can be imparted by water to objects of iron or steel.

It is believed that the errors in the observations of those who suppose they discover magnetism in water arise mainly from three causes. Although relatively few people are aware of it, many pocketknives are more or less magnetized, and it is not safe to assume without testing that a particular knife is nonmagnetic before it is placed in the water. Another cause of misinterpretation arises from the fact, also not generally known, that many well casings are magnetized, and that the magnetism attributed to the water is really due to the presence of this magnetic body in the vicinity of the knife tested. Still another cause of error lies in the fact that the knife is not wiped after being taken from the water and that the surface tension of the film of water on the damp blade may pick up a needle.

The following simple procedure, requiring no instruments, would go far toward settling the question of magnetism in natural waters. Take several pieces of steel and a number of needles which have been tested and found to be unmagnetized to a point 200 or 300 feet from the well or spring to be investigated, and after again testing steel and needles leave them, together with any other iron or steel articles about the person, at this point. Proceed to the well or spring and fill a large glass vessel with the water, and return with it to the steel and needles. Test these again and then place one of the pieces in the water in the glass vessel, leaving it there for five minutes. On removing the steel dry it and test it with a needle for magnetism. The experiment, if the magnetism is in any way connected with chemical changes in the water such as those depending on the passing off of the CO_2, should be made as quickly as possible. If found magnetic the steel and needle should be laid aside, care being taken that they do not come near the remaining pieces. If the water taken from the spring in a glass vessel shows no magnetism it may be desirable to test the spring itself for magnetism. To do this a previously tested piece of steel should be taken to the spring and left in the water for five minutes or more, after which it should be removed, dried, carried back to the base of operations, and again tested. If found magnetic the experiment should be repeated with a steel object left just outside the water limit at the spring. By a number of such tests the source of the magnetism, if any is present, can probably be located.

Of instrumental tests, that with the common compass is the easiest to make and consists in determining the distance from the well at which the needle is first found to be affected, and the distance at which it will point directly toward the well from the east or the west.

CAUSES OF MAGNETISM OF CASINGS.

The magnetism of well casings has been attributed to a number of causes, which include (1) the striking of magnetic bowlders, (2) the penetration of magnetite-bearing sands or rocks, (3) electric currents in the water, (4) magnetic material in suspension in the water, (5) chemical action of the water, (6) the interception of the magnetic lines of force in the earth, and (7) the production of induced magnetism by the motion of a magnetized drill.

Magnetic bowlders.—If magnetic bowlders were encountered by a drill or casing it is conceivable that they might impart magnetism, but although magnetite is common in bowlders of the glacial drift and is capable of being attracted by a magnet, it does not itself possess the property of magnetism, and it is difficult to see how a casing or drill striking such materials could become magnetic.

Magnetite sands or rock.—Many varieties of the crystalline rocks contain magnetite in fine particles, and when reduced by disintegration and decay, or by wave action, yield sands that abound in magnetite grains. These grains may be scattered through the drift or concentrated into thin beds or layers in stratified rocks. A well drilled in crystalline rocks, especially in the basic types, will generally encounter more or less crystalline magnetite, and even wells in drift and in stratified materials, both consolidated and unconsolidated, may encounter the included magnetite particles. The objection to this explanation of the derivation of magnetism is the same as to that of the magnetic bowlders, namely, that though the magnetite is attracted by a magnet it does not itself exhibit polarity and it probably can not induce magnetism in iron coming into contact with it.

Electric currents in water.—It is a matter of frequent observation that in cities electric currents entering the ground from trolley rails and other sources seek the water conduits, the iron casings being gradually destroyed by the process of electrolysis. Similarly it has been assumed that earth currents of electricity tend to follow the underground water conduits, and, although relatively weak, may impart magnetism to the casings through which the water is flowing. If magnetic wells were always flowing wells this might explain the phenomena, but in reality many magnetic wells, especially in the oil regions, including some even several thousand feet in depth, contain no water at all and contain oil only at the bottom.

Magnetic material in suspension in water.—Magnetic material held in suspension in water might be thought competent to magnetize iron or steel, but in reality particles in suspension lack the orientation necessary to induce magnetism. Moreover, there is no known source of such particles. Magnetite sand might be drawn in, but, as previously stated, can not induce magnetism. One chemist has asserted that the "magnetic" oxide may be precipitated in natural waters on standing, but even if this is true the precipitate does not possess magnetic properties.

Chemical action of water.—In chalybeate waters galvanic action is set up between brass or zinc well strainers and the iron casing, but there is no known means of producing the phenomena of magnetism in the iron by such a process. Besides, magnetism is found in wells not provided with strainers and independently of the quality of the water.

Induced magnetism from magnetic force of the earth.—As is well known, a steel body that remains for some time in one position may become distinctly magnetic owing to the polarization of its particles by the earth's magnetism. The strength of this action in wells should be proportional to the length of the casing, and as a matter of fact has been so found by William Richards, who has drilled many wells in Pennsylvania. On the other hand, some of the strongest magnetic wells yet noted are less than 100 feet in depth. The strongest arguments against such induced magnetism of the casings are (1) that the magnetism decreases rapidly after the completion of the well, and (2) that, according to Mr. Richards, pump tubes of equal length or longer than the casings do not become magnetic even when inclosed within an outer magnetized tube. Moreover, as will be pointed out in the next paragraph, the relation of length of casing to strength of magnetism can be explained otherwise than by direct induction.

Induced magnetism from drill.—That casings are not commonly magnetized by direct induction is probably due to the immobility of their particles. With the drill, however, these conditions are different. Through its rise and fall sharp vibrations are produced which tend to facilitate the readjustment of its molecules and their orientation according to the direction of the earth magnetism at that point. In some wells the drill when inserted was known not to be magnetic, but became so after being used a short time, even where no casing had been introduced. As this occurs in rocks where the other enumerated possible causes are out of the question, it seems certain that the magnetism of the drill has resulted in some such way as is here outlined. When, after the drill is magnetized, it is repeatedly passed in the process of drilling up and down through the casing in the same position and direction of movement it gradually imparts its magnetism to the casing. The larger the casing and the deeper the hole the more pronounced is the phenomenon.

In driving wells the casing itself may become directly magnetized, as in some materials the casing is forced downward only with great difficulty and by means of heavy driving weights, which set up vibrations much the same as those of the drill, and which possibly induce more or less magnetism.

CONCLUSIONS.

The magnetism exhibited by well casings is independent of depth, many shallow wells showing it as strongly as the deeper ones; it is not a question of material, for it is found in wells in all classes of materials. It is not due to electric currents nor to magnetic particles in water, as it is shown in wells without water as well as those filled with it, and it is not due to induction by earth magnetism, as it soon disappears after the completion of the well and is not found in the pump tubes. The casing is usually magnetized only when the drill is worked inside of it, a fact which explains the general absence of the phenomenon in granite and other rock wells in which the casing is carried only to the rock. This also explains why it is most common in deep cased wells, such as those of the Pennsylvania oil fields. Observation seems to indicate that the drill is the first to become magnetized, the casing showing magnetization later. The strength of the magnetization seems to be proportional, other things being equal, to the hardness of the rock. The facts briefly stated lead the writer to the conclusion that the phenomena are induced by earth magnetism aided by the vibration of the drill or of the casing when it is sunk by percussion, which permits the readjustment of the polarized particles of the steel.

UNDERGROUND WATERS NEAR MANASSAS, VIRGINIA.

By Frederick G. Clapp.

LOCATION AND GEOLOGIC ENVIRONMENT.

Manassas lies within and about 1½ miles west of the eastern border of the belt of Triassic sandstones which crosses northern Virginia. East of this belt the rocks are metamorphic and schistose in nature, with much contorted dips, generally at a high angle. The line of demarcation between the two areas crosses Bull Run at the mouth of Russia Branch, on the line of the Southern Railway, and extends in a direction slightly west of south along the west slope of Signal Hill. West of Manassas the Triassic basin extends nearly 20 miles to the Bull Run Mountains.

In the vicinity of Manassas the Triassic rocks consist of red sandstones of varying degrees of coarseness, lying nearly flat, with dips where measured of about 12°. The rock is well exposed in a quarry about half a mile northeast of town, where it is being worked for building stone, and in several small excavations along a public road a short distance east of the quarry. Where the direction of the dip could be seen it was about due north. In general the stone is massive and consists of beds 1 foot to 8 feet thick, being thinnest near the surface. The owner of the quarry reports that water is not found in the bedding or joints. The beds are cut by fine joint cracks, but where noticed these generally extend across one or two beds only. No trap dikes are known in the vicinity of Manassas, but some are reported a few miles away.

WELLS.

Owing to the considerable number of drilled wells at Manassas, fair opportunity exists for obtaining information regarding the occurrence of water in these rocks. Probably the best-known well is that drilled in the summer of 1905 for a public water supply. This well is situated close to the Southern Railway on the eastern outskirts of the town, in a slight depression, around which the hills rise 15 or 20 feet higher. Data supplied by members of the corporation of Manassas show that the well was drilled to a depth of 531 feet 8 inches, all but the last 6 or 7 feet through Triassic sandstone. At 525 feet a hard gray rock was struck, which continued to the bottom of the well and is supposed to be the metamorphic or crystalline rock that underlies the Triassic area. This well has a diameter of 8 inches to a depth of 200 feet from the surface, below which it is only 6 inches. It is reported to be cased to a depth of 180 feet. Two water-bearing beds are reported at depths of 210 and 487 feet, the deeper one supplying the greater amount of water. When the well was completed the water stood 58 feet from the surface. A 12 by 36 inch steam head pump was installed and a test of the well made, variously reported as lasting from six to ten hours, during which the well was pumped continuously. It is said to have yielded at least 120 gallons of water a minute, that being the full capacity of the pump. On account of lack of funds this well has never been used, but it is protected by a cement curb and housed over. Some persons have supposed that as this well is situated in a depression the water is liable to contamination, but if the casing extends to 180 feet, as reported, there is probably little danger.

On the Portner estate, on the northern edge of town, are half a dozen or more drilled wells, the deepest of which is 333 feet deep. The principal water is reported to occur in a coarse sandstone 220 feet from the surface. When this bed was reached the water, which had previously stood 24 feet from the surface, fell to 70 feet below the surface, where it remained, being unaffected by subsequent pumping. This well is pumped by a windmill and supplies enough water to maintain two fish ponds covering half an acre or more and to supply a bathing tank.

A few hundred feet to the north, near Mr. Portner's house, are two more wells about 100 feet apart. They are reported as being 215 feet and about 300 feet deep. They were connected by exploding a heavy charge of nitroglycerine in the bottom of one of them, establishing free communication for the water and permitting both wells to be pumped from one. A steam pump raises the water to a tank about 50 feet above the ground. These wells supply plenty of water for use of the house and stables. The water in the 215-foot well is said to have stood 60 feet from the surface and the principal supply to have come from a depth of about 200 feet.

A quarter of a mile or more still farther north, at Mr. Portner's stock farm, are two more wells. Both are said to be over 200 feet in depth and are pumped by a windmill. The water supplies 135 head of cattle, 20 horses, and 15 men, besides being used for cooling milk. These wells seem to show that there is plenty of water in the sandstones, if favorable localities happen to be found.

Mr. Prescott has a well said by him to be 200 feet in depth, in which the water stood 68 feet from the surface. The capacity of this well was only 8½ gallons a minute, but this is considered a good amount in that region, as it is sufficient for all domestic and ordinary farm purposes. Generally wells of moderate yield are tested with the sand pump.

A few hundred feet west of the Portner estate, on the road to Sodby Spring, are 3 deep wells, on the G. C. Round, Taylor, and Lipscomb properties. They are 145, 115, and 140 feet deep, respectively, and all yield water enough for domestic purposes. Mr. Taylor reports 10 gallons a minute from his well and 20 gallons a minute from the Lipscomb well. The following is a record of the Taylor well, as reported by the owner:

Record of Taylor's well, Manassas, Va.

	Thickness.	Depth.
	Feet.	*Feet.*
Soil, etc.	8	8
Slate	2	10
Brownstone	30	40
Sandstone, gray	50	90
Coal	1+	91+
Sandstone, gray		

The water is reported to occur in a coarse sandstone 1 or 2 feet thick at the bottom of the well, and the same stratum is supposed to furnish the water in the Lipscomb well, on the lot next to the north. This water has been analyzed by the Bureau of Chemistry of the United States Department of Agriculture.

South of Manassas, about half a mile from the railroad station, is a well 102 feet deep on the W. H. Morann place. This well procures water from a coarse bed 100 feet from the surface and is piped to supply four houses in the vicinity. In dry weather this well has been utilized to the full capacity of the pump and has never given out.

According to reports of the drillers and owners no well drilled in the Triassic area in the vicinity of Manassas has failed to find water within a depth of 100 to 200 feet, although some of them yield only a few gallons. So far as can be judged by reports, the water occurs at no particular horizon, although some wells near together seem to have a water horizon in common. The water generally occurs in a coarse bed of sandstone. In many wells near town the drillers report a "grindstone rock," which is said to average 20 feet in thickness and to be irregular in occurrence. It may be a dike, but this is very doubtful. "Flint rock," perhaps a hard limestone, is frequently reported. In quality the water varies considerably, both hard and soft water being found. It is commonly believed that the water is harder in the lower strata than in the upper, and softer at the east end of town than at the west end; for this reason the corporation well was located at the east end.

A rather interesting well is that of Libeau Brothers, situated on the southern border of Manassas. This is a dug well 75 feet deep and 5 feet in diameter at the surface, but increasing downward to 19 feet at the bottom. A large supply of water, which filled the well within 6 or 7 feet of the surface, was found in a bed of very soft sandstone near the bottom. As the well stands on rather low ground, it is probable that some of this is surface water.

Few data are available regarding water in the rocks outside the Triassic area. All the information at hand is derived from observations on Signal Hill, just east of the contact. This hill is about 2 miles long and is surrounded by numerous springs, which some persons have supposed to be of deep-seated origin, but their volume is so small that they are probably all derived from the rainfall on the hill. Mr. Dickens has a well 62 feet in depth, in which water stands 20 feet from the surface. It is reported to have a capacity of 6 gallons a minute.

WATER SUPPLY OF MANASSAS.

At present practically all the well-to-do families in Manassas have satisfactory deep wells of their own, but for those who have not and for use in case of fire a public supply is needed.

The population of Manassas in 1900 was 817, but since that time it has increased slightly. If the present population is 1,000, and 60 gallons a day per capita is the maximum amount of water which would probably be consumed, 60,000 gallons ought to be sufficient for domestic purposes alone. The quantity of water necessary for fire protection must, of course, be added to the 60,000 gallons. Of course it is important to consider the need resulting from probable increase in population, but this will probably be offset for some time by the number of persons who have deep-well supplies of their own.

To provide the necessary water the corporation well, mentioned above, was drilled in 1905. If the test of this well is reliable, it will yield at least 120 gallons a minute, or 172,800 gallons a day, nearly three times the amount necessary for a population of 1,000. It seems very probable, however, that this capacity will not continue indefinitely, and if the supply is found inadequate another well will have to be drilled. Certain persons in the town have urged going to Signal Hill, or even to the Blue Ridge, for the town supply, but such an expense seems unnecessary. A well at a given spot is not certain to obtain water in quantity, as some wells furnish only a few gallons each, but if one well does not succeed another should be tried near by.

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UTILIZATION OF THE UNDERFLOW NEAR ST. FRANCIS, KANSAS.

By Henry C. Wolff.

INTRODUCTION.

In August and September, 1908, investigations were carried on in the valley of South Fork of Republican River, near St. Francis, Cheyenne County, Kans., to determine the quantity of the underflow water and the possibility of recovering it for use in irrigation. This report embodies the chief facts obtained in the field work, together with suggestions for installing small pumping plants to recover the ground water.

Only a few years ago a large part of this valley formed one big cattle ranch, but at present it is divided into a number of ranches of moderate size, and increasing attention is being given to agriculture. About sixteen small irrigation ditches now take water from the river within 10 miles of St. Francis.

The soil of the bottom lands differs in quality from place to place. Certain areas are too sandy or too moist for cultivation and are better suited for pasture and hay lands, but the soil of a large part of the bottoms is excellent and is well suited to alfalfa and other crops. The best tracts of land lie between poorer sandy strips, an arrangement which is of great benefit in the development of the valley by irrigation, for it tends to make it practicable to irrigate all the better lands without overdrawing the sources of supply.

During times of light precipitation, high evaporation, and large draft on the ground water by growing vegetation the water plane often drops below the bed of the river and the stream runs dry. Thus the lack of river water for irrigation when it is most needed has led the farmers of the valley to consider the possibility of installing pumping plants.

The field work on which this report is based consisted of putting down test holes in the bottom lands through the alluvial deposit to shale, of making underflow velocity measurements, of collecting samples of sand and water for analyses, and of determining the slope of the water plane.

Acknowledgment must be made of the interest manifested and the assistance given by the people of St. Francis and vicinity. Not only did they aid the writer in every possible way, but through the Commercial Club of St. Francis they supplied all the necessary common labor required for the investigation.

THE UNDERFLOW.

WATER-BEARING MATERIAL.

South Fork of Republican River crosses the northwest corner of Kansas, flowing in a northeasterly direction. The river has cut down several hundred feet through the loess and Tertiary deposits of the high plains into the Pierre shale. In the bottoms this shale is covered to a depth of 15 to 20 feet with water-bearing sand and gravel derived from the disintegrated Tertiary deposits. The river flows for the most part upon this sand and gravel through a natural meandering channel formed by cutting away the upper portion of the deposit. Because of the shallowness of the gravels and the presence of the underlying impervious shale the stream has an unusually strong tendency to survive throughout the summer months. At places where the shale comes near the surface the stream bed is rarely quite dry, presenting a marked contrast to most of the streams in western Kansas, which disappear entirely at times during the summer. The river has many western tributaries that flow through canyon-like valleys, and these tributaries also show a strong tendency to maintain a summer flow. Similar draws entering the valley from the east are usually dry in summer and are not important feeders of the river.

Although the great part of the work was done near St. Francis, a few test holes were sunk along the valley for a distance of 10 miles above to 14 miles below that city. Within this distance the bottom lands range in width from half a mile to about 3 miles, this being also the approximate width of the alluvial deposits. The water-bearing material ranges in thickness from 10 to 25 feet and in most places consists of gravel that is adapted to well construction, containing enough coarse material to warrant the use of a well strainer having perforations as large as 1¼ inches long by three-sixteenths inch wide. Near the center of the valley the gravel is very clean and contains but little very fine material. Toward the edges of the valley the percentage of fine sand markedly increases and earthy material, probably washed down from the banks and uplands, becomes noticeable.

WATER PLANE.

Figure 23 shows the location of most of the test wells put down at St. Francis and of three private wells concerning which data were collected. The downward slope of the water plane at this point was found, from measurements of its elevation at stations Nos. 5, 4, and 12, to be 10.7 feet a mile to the northeast, as indicated by the arrow in the drawing.

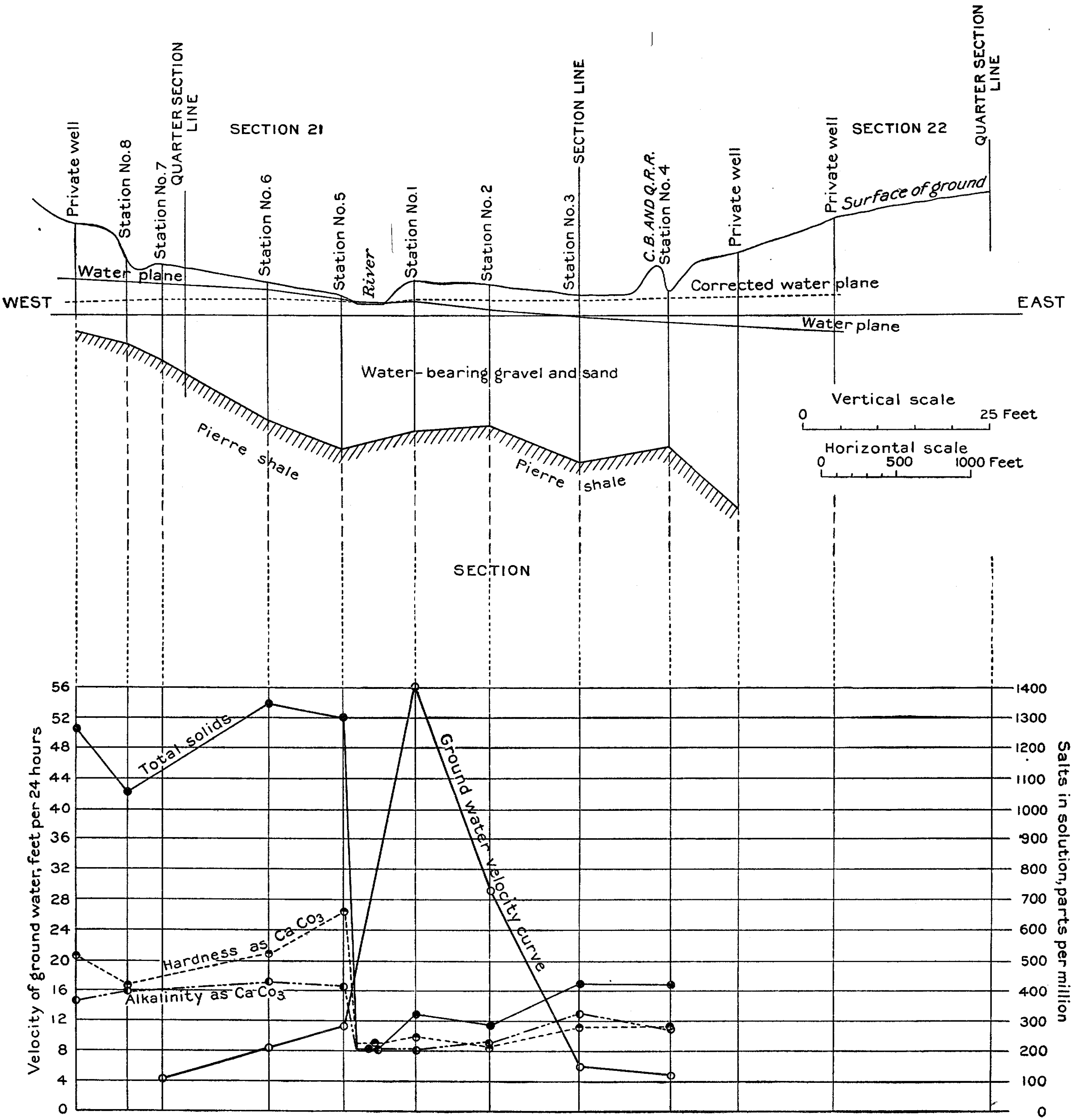
Plate II shows a cross section of the river valley along the east and west line of test wells at St. Francis. The vertical scale in this drawing is very greatly magnified, being 50 times that of the horizontal. The surface of the ground, the upper surface of the Pierre shale, the true water plane, and what is called the corrected water plane are all represented. The true water plane, shown by a full line, was determined by running levels to the test holes and private wells, and proved to have a decided downward slope from west to east. This slope was to be expected, for by referring to figure 23, the line of test wells from west to east is seen to be not normal to the channel, but to extend at an angle of about 45° to the general direction of the valley. Thus the wells at the east end of the line are farther down the river, and the water in them should stand lower than in the wells farther west. By correcting the measured elevations of the ground water along this line the dotted line in Plate II, marked "corrected water plane," is obtained. This line shows the position of the water plane along a line drawn at right angles to the direction of the valley, a position that is, in general, nearly level. At all points the movement of the underflow is down the valley, with no lateral components.

The upper part of figure 24 shows the location of a line of test wells 10 miles above St. Francis. The lower part is a cross section along the line of wells, showing the position of the shale and of the water plane. At this point the river has cut down nearly to the shale and has drained the water from the neighboring sands and gravel.

VELOCITY.

In figure 23 the arrows drawn from stations Nos. 1 to 7 represent in magnitude and direction the velocity of the underflow at these seven points. The numbers at the ends of the arrows represent the velocity in feet per twenty-four hours. The direction of the underflow follows very closely that of the river valley, which at this point is approximately 45° east of north.

In the lower part of Plate II the ground-water velocities are again represented graphically and may be read by the scale at the left, on which the vertical distance represents velocity in feet per twenty-four hours. The horizontal elements represent distances between test holes, as marked at the top of the drawing. From this



CROSS SECTION OF THE ARKANSAS VALLEY NORTH OF ST. FRANCIS, KANS.

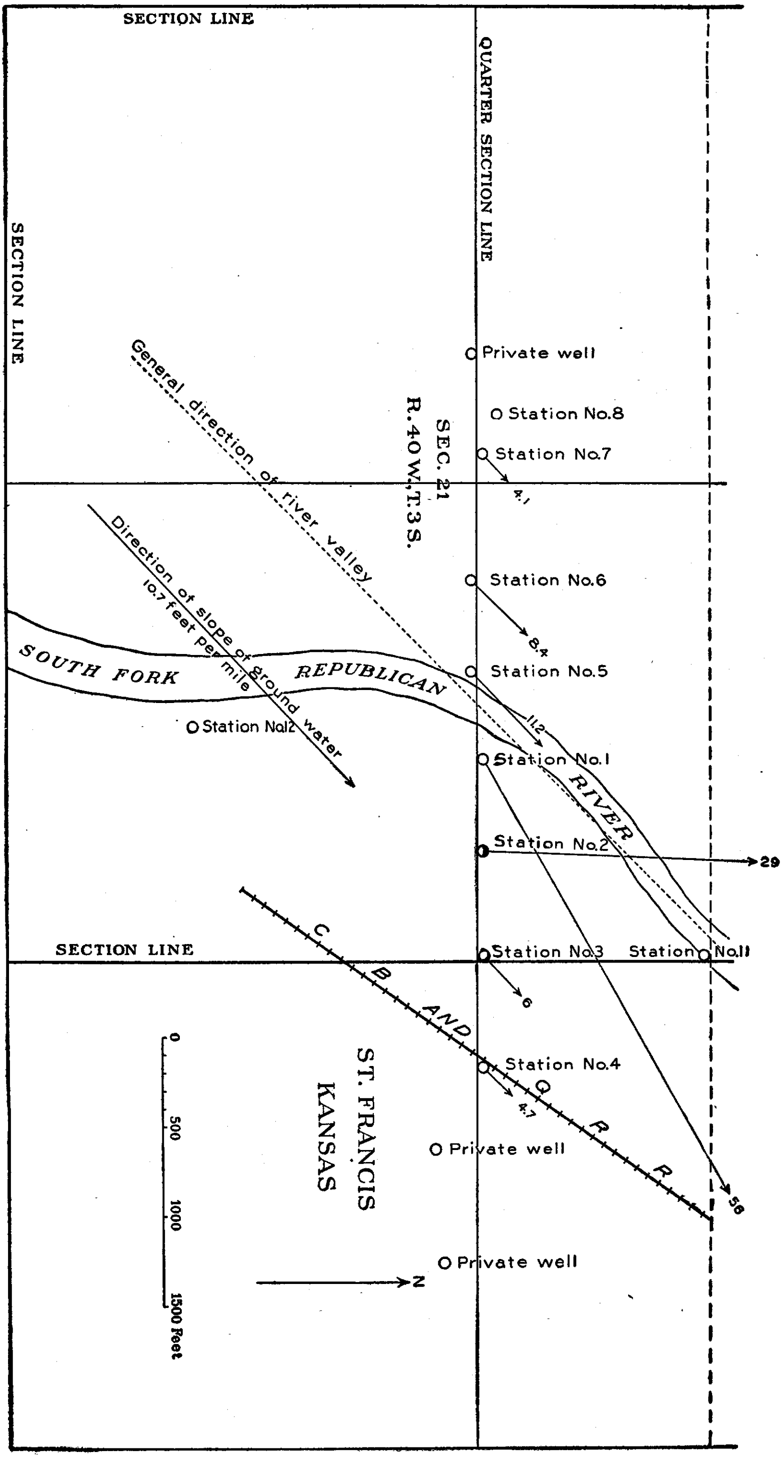


FIGURE 23.—Map showing location of test wells at St. Francis, Kans.

it will be seen that the velocity of the ground water drops from 56 feet per twenty-four hours near the center of the valley to about 4 feet per twenty-four hours at the edges of the bottom lands. This decrease is due principally to an increase of fine silt and claylike material in the water-bearing gravel from the center of the valley toward the edges of the bottom lands. Observations of the gravels taken from test holes sunk in the valley show that a similar variation occurs in any cross section of the bottom lands below St. Francis. This ground-water velocity curve represents in a general way the relative capacity of wells sunk along the line of the section. Therefore, other things being equal, a well sunk to obtain water for irrigation should be placed as near the center of the valley as practicable.

The average velocity of the underflow is 17 feet per twenty-four hours. If this rate of flow be divided by the slope of the water plane, expressed in feet per mile, the quotient is 1.6. This is the average velocity of the ground water that might be expected if the water plane had a slope of 1 foot to the mile. The corresponding factor for the underflow of the Arkansas River valley at Garden, Kans., is 1.1, which indicates that wells in the Republican River valley would have a somewhat greater capacity than those at Garden. The same indication is given by the general appearance of the water-bearing gravel, although no mechanical analyses have been made of the samples taken.

The area of the cross section of the water-bearing gravel at St. Francis, as shown in figure 24 and Plate II, is 71,500 square feet. This area, with an average normal underflow velocity of 12 feet per twenty-four hours and a porosity of one-third for the water-bearing material, would give a total flow of 3.3 cubic feet per second, or 1,485 gallons a minute, about the equivalent capacity of four 4-inch centrifugal pumps. These figures are given as an answer to the question often asked, "Would it not be feasible to construct a subsurface dam across the river to intercept the underflow and bring it to the surface?" Even if the cost of such a dam were neglected, a cost which alone puts it out of consideration, it would result in an inelastic system, yielding only 3.3 cubic feet per second continuously, and this yield could not be increased without using pumps.

REPLENISHMENT.

It is often asked (1) how it is possible for a well to yield any appreciable amount of water with so small an underflow, and (2) whether a large number of pumping plants simultaneously operating during the dry season would not exhaust the underflow in a few seasons.

In considering the first question it must be remembered that for slow velocities the flow is directly proportional to the hydraulic gradient, and that in the neighborhood of a pumped well this gradient is increased when the pump is in operation from a few feet per mile

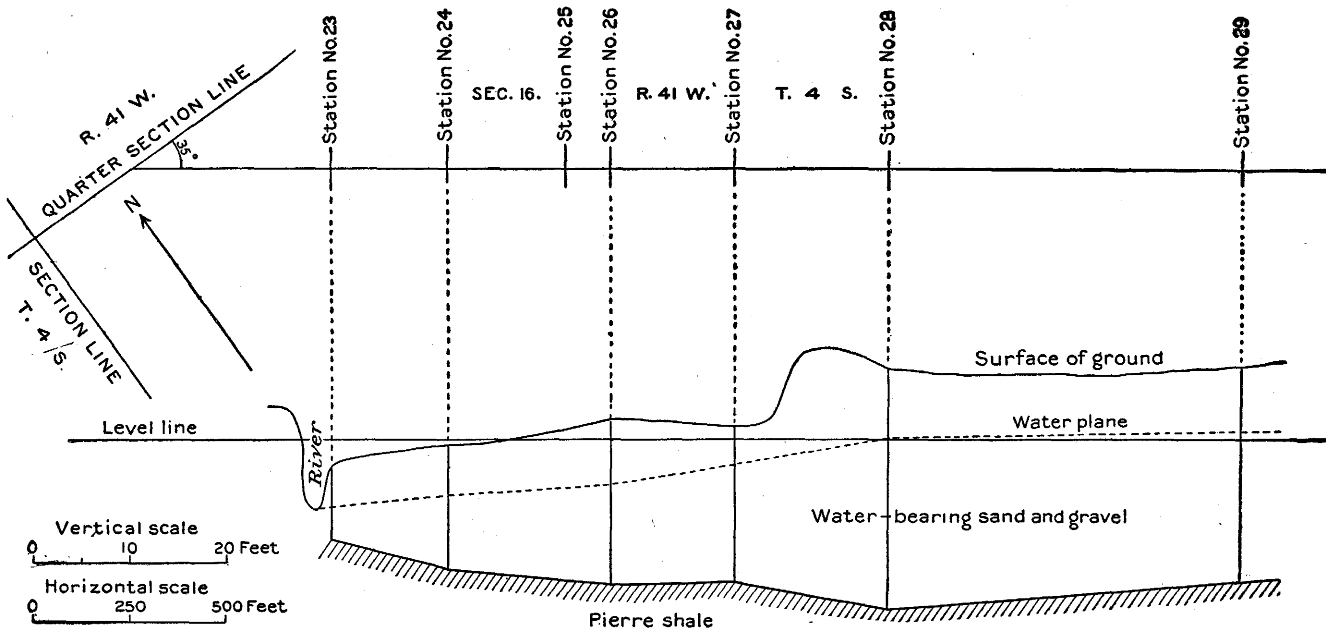


FIGURE 24.—Location of test holes 10 miles above St. Francis and cross section showing position of the shale and of the water plane.

to perhaps the same number of feet per yard. Figure 25 represents the depressions of the water plane in the neighborhood of a 15-inch well in the Arkansas River valley near Deerfield, Kans. Each curve represents the position of the water plane after seven hours continuous pumping, the pump being so gaged as to hold the drawdown of the water in the well pumped at 2.2, 4, 6.4, 8.6, and 11.7 feet below its normal position. The curves are replotted on logarithmic paper in figure 26, and here become straight lines, whose equation may be determined. This well was provided with an 8-foot strainer and under the heads named furnished, respectively, 31, 59, 94, 121, and 152 gallons a minute. These relations between yield and draw are plotted in figure 27, from which it will be seen that for drawdown of less than 7 feet the yield was directly proportional to the distance the water was lowered. Beyond this point the increase in yield for each additional foot of pressure grew smaller, as shown by

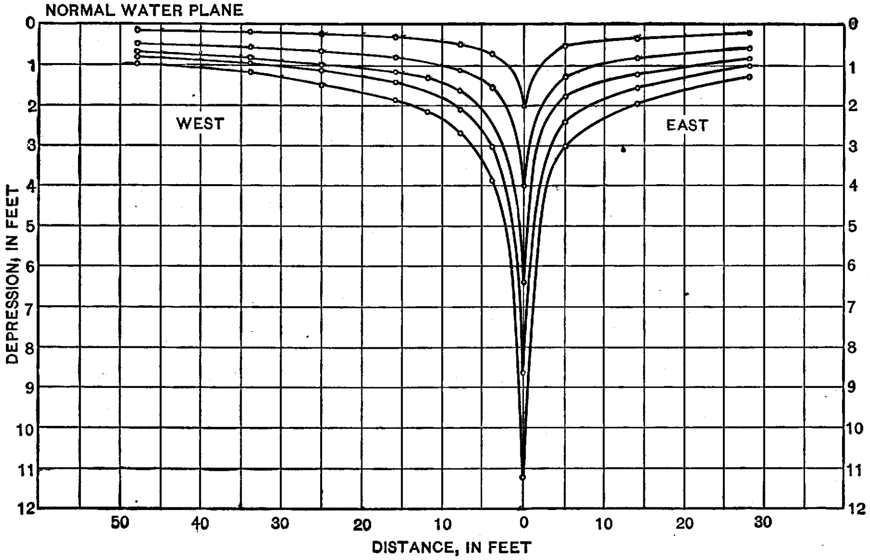


FIGURE 25.—Curves showing position of water plane near a 15-inch pumped well in the Arkansas River valley near Deerfield, Kans.

the bending of the curve above the straight line. The yield is therefore plentiful.

There need be no fear that the ground water will be exhausted in any number of seasons. Suppose that on each section or square mile of the bottom lands there are a number of plants pumping constantly night and day at the combined total rate of 1,000 gallons a minute for one hundred consecutive days; and suppose also that during this time there is no precipitation, that the river is perfectly dry, and that none of the water used for irrigation finds its way back to the underflow, so that there is no replenishment of the ground water; then the ground-water plane would be lowered about 2 feet. The

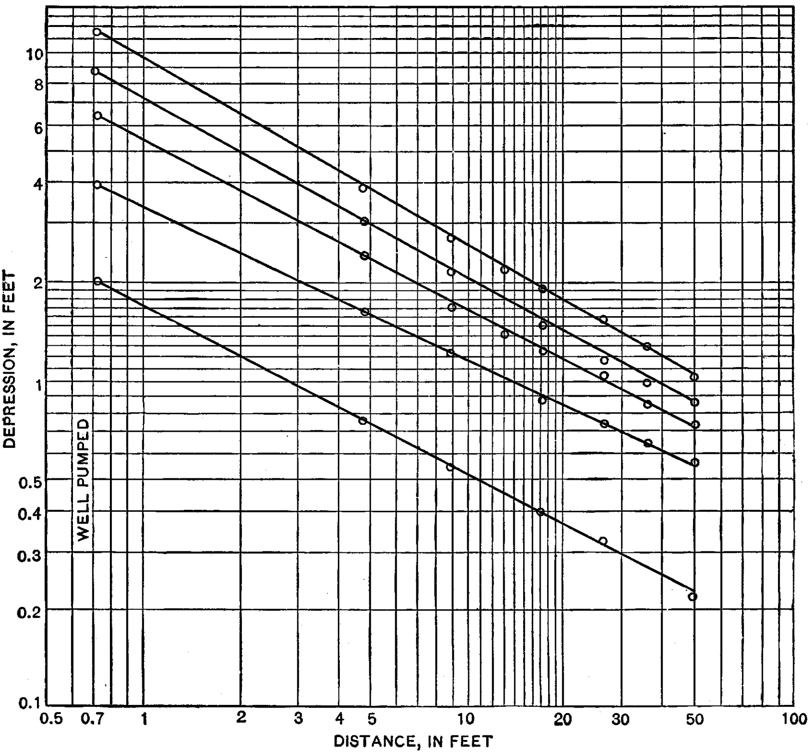


FIGURE 26.—Logarithmic representation of data in figure 25.

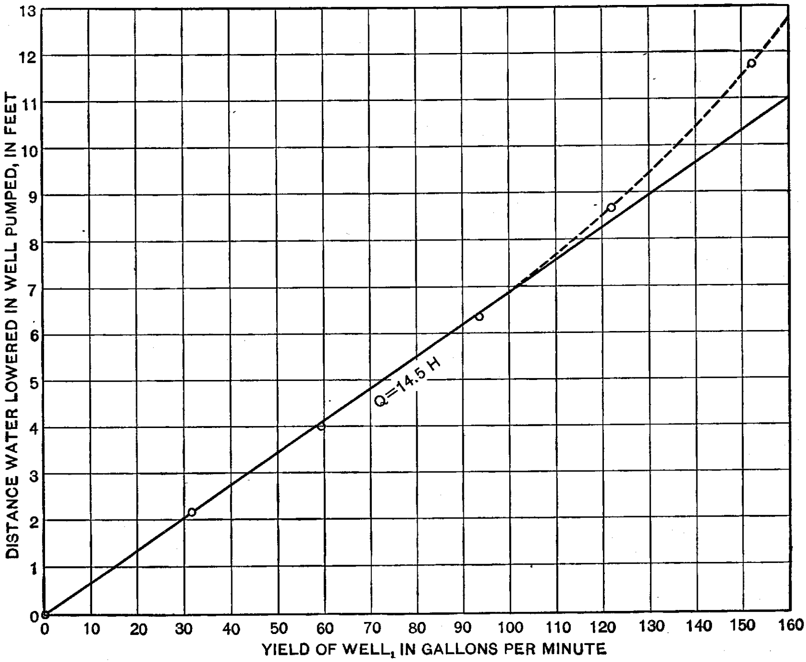


FIGURE 27.—Curve showing relation between yield and drawdown in a 15-inch well in the Arkansas River valley near Deerfield, Kans.

water thus recovered would irrigate two-thirds of each section to a depth of 1 foot. If the water plane were thus drawn down below the bed of the river, part, if not all, of the overflow passing St. Francis would not reach Benkelman but would join the underflow by sinking into the loose sandy bed of the river. The farther the ground water is lowered the faster will this transfer from overflow to underflow take place.

TABLE 1.—*Estimated discharge of South Fork of Republican River at Benkelman, Nebr., 1903–1906.*[a]

Month.	Discharge in second-feet.			Total (acre-feet).
	Maximum.	Minimum.	Mean.	
1903.				
May (20–31)	57	36	48	1,140
June	65	7	37	2,200
July	36	7	15	922
August	79	7	25	1,540
September (1–5 and 14–30)	22	7	15	655
October	50	7	39	2,400
November (1–20)	65	50	57	2,260
1904.				
March	102	31	60	3,690
April	66	6	21	1,260
May	255	47	92	5,680
June	397	47	132	7,850
July	115	5	39	2,420
August	89	11	24	1,480
September	47	5	13	774
October	115	31	57	3,540
November	66	47	59	3,530
1905.				
March (17–31)	249	96	159	4,730
April	300	52	141	8,390
May	137	52	100	6,150
June	283	21	68.6	4,080
July	152	5	35.4	2,180
August (1–13)	96	21	47.7	1,230
1906.				
April	317	73	129	7,680
May	215	52	99.3	6,110
June	52	0	90.3	5,370
July	183	0	10.9	670
August	0	0	0	0.0
September	0	0	0	0.0
October	61	0	21.8	1,340
November	61	36	48	2,860

[a] Water Supply Papers U. S. Geol. Survey Nos. 99, 130, 172, and 208.

TABLE 2.—*Average monthly discharge of South Fork of Republican River at Benkelman, Nebr.*

Month.	Number of observations.	Discharge.	
		Acre-feet (on surface).	"Section-feet" of ground water.
April	3	5,770	27.0
May	2	5,840	27.4
June	4	4,880	22.9
July	4	1,530	7.0
August	3	1,480	6.9
September	2	390	1.8
October	3	2,400	11.2
November	2	3,180	14.9
		25,470	119.1

A United States Geological Survey stream-gaging station is located on South Fork of Republican River near Benkelman, Nebr., where gagings were taken during a part of each year from 1903 to 1906. The estimated discharge of the river at this point is shown in Table 1. By averaging the monthly discharges in acre-feet for the four years the figures given in Table 2 were found. The third column of this table gives the average estimated discharge by months in acre-feet—that is, the number of acres the water would cover to a depth of 1 foot. The fourth column gives the same discharge in "section-feet"—that is, the number of sections of 640 acres each on which the ground water would be raised 1 foot if all of the water went to replenish the underflow, the gravels having a porosity of one-third. The data in this table are also presented graphically in figure 28. During the four months in which the river was not gaged—December, January, February, and March—as much if not more water flows away from the valley of the South Fork. Altogether the supply would suffice to raise the ground water 1 foot on 240 sections—that is, it would be 50 per cent more than would be necessary to replenish 80 sections if lowered 2 feet by pumping. This estimate is believed to be moderate, for, first, the time will probably never come when 80 sections of bottom land will be irrigated by pumping from the underflow; second, a portion of the water used for irrigation (probably more than 20 per cent) will find its way back to the ground-water supply; third, the local precipitation will increase the supply not only by the amount that falls directly upon the bottom lands but by the amount that drains into the valley from the hills on either side; and fourth, it is probable that the total discharge of 51,000 acre-feet per year for South Fork of Republican River is too small rather than too large.

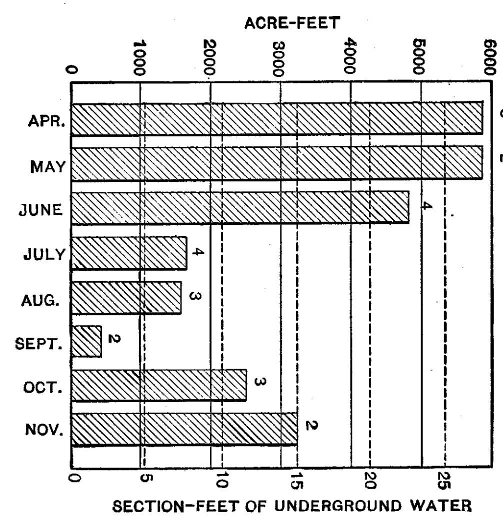


FIGURE 28.—Average monthly discharge (estimated) of South Fork of Republican River at Benkelman, Nebr.

The amount of water that escapes over the surface during the winter and spring floods is large in proportion to the size of the valley; the alluvial deposits afford about the only means of storing these flood waters, and their ability to perform this service is increased by pumping.

SPECIFIC CAPACITY.

At the time of the ground-water investigations only one pumping plant was recovering water for irrigation along South Fork of Republican River. This plant is in the SE. ¼ SW. ¼ sec. 9, T. 1 S., R. 38 W. It consists of an 8-horsepower gasoline engine, a centrifugal pump, and a 15-inch well. The well casing is made of 20-gage galvanized sheet iron, the lower 10 feet perforated to admit water. The perforations are vertical slits, perhaps 1 inch by one-fourth inch, 1 inch apart, placed in vertical rows about 1 inch apart. The casing extends down to shale, 24 feet below the surface of the ground, or 14 feet below the normal water level.

On September 16, 1908, after the plant had been in operation day and night for several days, the yield of the well was determined by pumping continuously for three hours into a reservoir. During these three hours of pumping the water rose in the reservoir 1.54 feet, to which must be added 0.24 feet for loss by seepage. The area of the water surface at the beginning of the test was 2,266 square feet and at the end 2,497 square feet. This gives a yield of 176 gallons a minute.

During the test the water in the well stood 12.5 feet below its normal level. Dividing the 176 gallons by 12.5 gives 14.1 gallons a minute for each foot of draw down of the water. This quantity is termed the specific capacity of the well. Dividing the specific capacity (14.1 gallons a minute) by 39.24, the total percolating area of the well casing in square feet, gives what is termed the specific capacity of the gravels; in this case 0.36 gallon a minute. The specific capacity is a factor expressing the readiness with which the gravel yields water to a well. In other words, it is the yield in gallons a minute of a well having 1 square foot of strainer surface when the water in the well is lowered 1 foot below its normal position. The specific capacity of this well would probably have been very greatly increased if the strainer end of the casing had been more closely perforated, so as to admit the water into the well more freely.

The specific capacity of the gravels in Arkansas River valley, near Garden City, Kans., runs from 0.11 to 1.3, the average of 12 tests being 0.41.[a] The specific capacity of the Richardson well compares favorably with these capacities, and a comparison of the water-bearing material in the two valleys indicates that the specific capacity of wells in the South Fork of Republican Valley may be greater than those in the Arkansas Valley.

[a] Slichter, C. S., The underflow in Arkansas Valley in western Kansas; Water-Supply Paper U. S. Geol. Survey No. 153, 1906, p. 56.

QUALITY.

Samples of ground-water taken from various wells in the valley were tested for chlorine with tenth-normal silver nitrate, for alkalinity with tenth-normal hydrochloric acid, for hardness with a standardized soap solution, and for total solids in solution by means of a Whitney electrolitic bridge. The results of these tests are given in Table 3 and are represented graphically in the lower part of Plate II. At St. Francis the total solids in solution run as high as 1,350 parts per million, whereas 600 is about the ordinary limit allowable for water to be used for irrigation. Nevertheless, with the exception, perhaps, of some of the water found along the northwest edge of the valley, these amounts are not large enough to be injurious to plant life, for the soil of the valley is of loose texture and lies upon a sandy subsoil, and the salts in solution are not the kind most injurious to plant life.

TABLE 3.—*Data concerning wells at stations at St. Francis, Kans., and 10 miles above St. Francis.*

Station.	Depth to shale.	Depth to water.	Velocity of underflow.	Chemical analyses of ground water.				Elevation of water plane above assumed datum plane.
				Total solids.	Chlorine.	Alkalinity.	Hardness.	
	Feet.	*Feet.*	*Feet per 24 hours.*	*Parts per million.*	*Parts per million.*	*$CaCO_3$ (parts per million).*	*$CaCO_3$ (parts per million).*	*Feet.*
At St. Francis:								
1	19.5	2.0	56.0	320	9	200	251	92.01
2	18.5	2.0	29.0	290	9	225	220	90.69
3	22.0	2.5	6.0	420	12	315	283	89.79
4	21.0	3.5	4.7	420	30	275	283	89.17
5	20.0	1.4	11.2	1,300	99	410	662	92.10
6	20.0	1.7	8.4	1,350	43	430	514	93.12
7	13.5	1.4	4.1					94.12
8	11.0	.5		1,050	37	396	407	
11								87.80
12	20.5	5.5						94.18
13	20.0	3.0						115.28
River				300	9	220	216	91.69
Finley				1,250	43	265	508	94.70
Ten miles above St. Francis: [a]								
23	7.5	2.5						95.0
24	13.0	5.4		360	10	265	280	94.2
26	17.5	6.8		380	12	262	255	95.3
27	18.0	5.0		340	10	260	299	96.1
28	22.5	9.6		290	9	205	292	100.4
29	22.0	8.2						99.3

[a] The elevations of water plane for stations 10 miles above St. Francis are referred to a second arbitrary datum plane.

PUMPING PLANTS.

GENERAL STATEMENT.

The investigations made in the valley of the South Fork of Republican River indicate that in almost any part of the bottom lands between St. Francis and Benkelman an ample supply of ground water can be had for small pumping plants. The water-bearing gravels have an average thickness of 15 to 20 feet and contain enough coarse material to render it unnecessary to use fine-mesh strainers in the wells. In a large part of the bottom lands the depth to water ranges from 2 to 10 feet, so that the water may be pumped to the surface economically. The cost of pumping at any place will be controlled primarily by the cost of fuel and the distance the water must be lifted; and the answer to the question whether a pumping plant may be profitably installed must depend largely on the crops that can be grown and the prices at which they can be marketed.

CHARACTER OF WELLS.

The cheapest well for procuring ground water in the large quantities needed for irrigation is one that is from 12 to 15 inches in diameter and that extends through the water-bearing gravels to the Pierre shale, and, if practicable, for 2 or 3 feet into the shale. A strainer for such a well can be made by punching sheets of heavy galvanized iron with slots about one-eighth by 1 inch in size and then riveting the sheets into cylinders. The cylinders should be so rolled that the burr made by the punch will be inside the cylinder and the long diameter of the slots will be vertical in the well. A much better strainer can be made of metal purchased in sheets already perforated. Steel sheets 48 by 60 inches, perforated with hit-and-miss slots three-sixteenths by 1 inch and then galvanized, make ideal strainers. When rolled into cylinders these sheets form sections of a casing about 15 inches in diameter. In constructing the well these perforated sections should be put in place, one above another, to a point about 8 feet below the water level; from this point upward the casing should not be perforated.

AMOUNT OF WATER OBTAINABLE.

Wells constructed as just described will furnish at least one-third gallon of water a minute for each square foot of strainer surface in the well when the water in the well is lowered 1 foot by pumping. If the water in the well is lowered 10 feet by pumping, the quantity of water recovered should amount to about ten times as much, or 3.3 gallons per square foot of strainer. If a 15-inch well, the lower 10 feet of which is strainer surface, is placed in good water-bearing gravel, and if the pump lowers the water in the well 10 feet, the amount of water supplied by the well should amount to about 133 gallons a minute.

A 15-inch well in the Arkansas River valley (see fig. 27) has a capacity of 136 gallons a minute with 10 feet of drawdown. The gravel in which this well was sunk was not so good a water-bearer as some of that in the valley of Republican River.

A 9-inch well with an 8-foot strainer in the Cimarron River valley, Beaver County, Okla., sunk in ordinary clean gravel, such as is found near the center of the valley at St. Francis, had a capacity of 265 gallons a minute when the water plane was lowered 8 feet by pumping. Wells of this capacity could probably be sunk at two or more places where test holes were put down near St. Francis.

In the Republican River valley the yield of wells differs greatly. One well only a few hundred yards from another may furnish two or three times as much water. A small amount of the fine earthy material mixed with the sand and gravel will greatly cut down the yield. This fine material, usually loess washed down from the uplands, is found near the edge of the valley, especially where a draw or creek comes down from the uplands. As a general rule, the nearer a well stands to the center of the valley the greater is its capacity. In locating a pumping plant it is desirable first to put down a series of test holes in order to find good water-bearing material, especially if the plant is to be located near the edge of the valley or near the mouth of the creek.

METHOD OF SINKING WELLS.

Wells of diameters of 12 or 15 inches may be best sunk with an 8-inch or 10-inch sand bucket. As the sand is pumped out the casing is weighted at the upper end with sacks of sand and allowed to settle.

A pit should be dug to the water plane, or as deep as possible. Within this a larger temporary blank casing should be sunk 8 to 10 feet below the water plane. Within this temporary casing the permanent well casing and strainer should be placed and pumped down with the sand bucket. By this method the strainer part of the well will be sand-pumped down through the gravel from which water is to be drawn, and by the churning of the sand pump the gravel for several feet around the well will be washed free from a large part of the fine material which it contains. This is one reason why a strainer with large openings should be used. It will take more time and patience to sink a well in this way than to sink the unperforated temporary casing to shale and place the permanent casing inside, but if the velocity of the entering water is great there is a compensating gain in the removal of the fine material around the casing.

Care should be taken that the lower end of the permanent casing is well within the shale, so that there will be no possibility that sand will be drawn into the well when the pump is started. After the final casing is in place the outer temporary casing should be slowly pulled out, and as it is withdrawn coarse gravel should be fed in, a little at a time, between the temporary and final casings. Care must be taken that the inner portion does not bind to the outer, so that both casings will be lifted. After the outer casing has been drawn it will probably be found that the well has filled up several feet with sand. This sand should be pumped out with the sand bucket. The end of the suction pipe should be placed as near the bottom of the well as possible, in order to remove any additional fine sand that might find its way into the well, which should be very little if the well is put down as described above. The object of digging the pit to ground water and inserting a temporary casing is to shut off the fine sand which is generally found above and for a short distance below the water plane, and to make it necessary to raise the sand bucket but little, if any, above the surface of the ground.

ARRANGEMENT OF WELLS.

At no place in the valley will it be possible to supply a 4-inch centrifugal pump from a single well. Three or four wells that yield 140 gallons a minute each should be connected with a single pump. The more wells used the less will the water plane be lowered and consequently the less the work that will be required of the engine and the less the fuel consumed. Not all of the reduction in the lift of the water is gain, however, because power will be lost in overcoming the friction due to the additional length of piping connecting the wells.

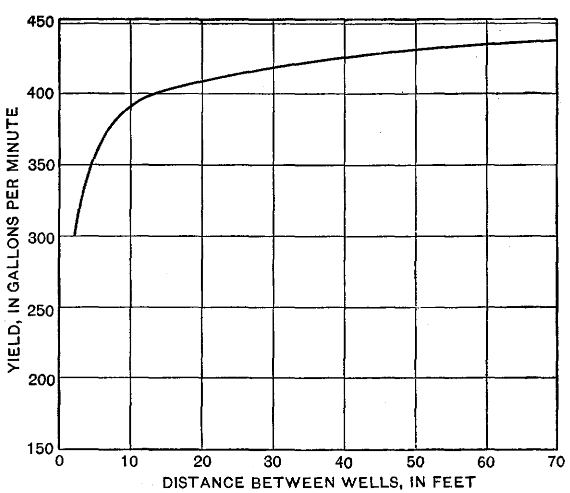


FIGURE 29.—Relations of three wells in the Arkansas Valley.

Since it is necessary to construct several wells in order to obtain the quantity of water required for an irrigation plant it becomes important to consider the best and most economical arrangement of the wells. In the Republican River valley perhaps the best method is to sink a battery of three or four wells and connect them by suction pipes to the pump. These wells should be arranged in a line and placed 20 to 30 feet apart, with the pump near the middle of the line. Figure 29 represents in a rough way the interference of three wells with different spacing and shows why the wells should not be placed nearer together than 20 to 30 feet. If the water plane is lowered the same amount at all times, say 10 feet below the normal position, and the three wells are placed so far apart that there is no interference, their total yield will be 450 gallons a minute. If the wells are 40 feet apart, the yield will drop down to 425 gallons; if 30 feet apart to 420 gallons; if 20 feet apart to 415 gallons; and for a nearer spacing than 20 feet the yield would be considerably lessened. The construction of a plant having four wells is given in figure 30.

SELECTION AND INSTALLATION OF PUMPS.

It does not pay to purchase any but the best machinery for pumping, as poorly designed and poorly constructed plants eventually prove very expensive.

Probably the most satisfactory pump for use in irrigation is the centrifugal pump. It should be remembered, however, that there are on the market a great many kinds of small centrifugal pumps, which are designed for a great many purposes. The centrifugal pump used by the irrigator should be of the inclosed-runner type, provided with self-oiling bearings of the oil-ring type. Several pumps of this type can be had, and any of them will do good work if its size and design are adapted to the conditions under which it must work. The maker of the pump should have full information of all the conditions, including the distance that the pump must discharge the water above its outlet and the amount of suction or distance the water must be lifted below the pump inlet.

The efficiency of the centrifugal pump under actual working conditions is higher for large pumps than for small ones. Pumps having a discharge pipe less than 3 inches in diameter will show low efficiency. A centrifugal pump will work better and be more efficient if the suction pipe is made as short as possible, and on this account the pump should be placed as near the level of the water as may be consistent with the securing of a good foundation.

If the pump is to be driven by a belt it should be provided with a large pulley. The pulley usually supplied with a pump is so small that the belt slips on the pulley, so that the efficiency of the plant is greatly decreased. Of course, it is necessary to maintain a proper

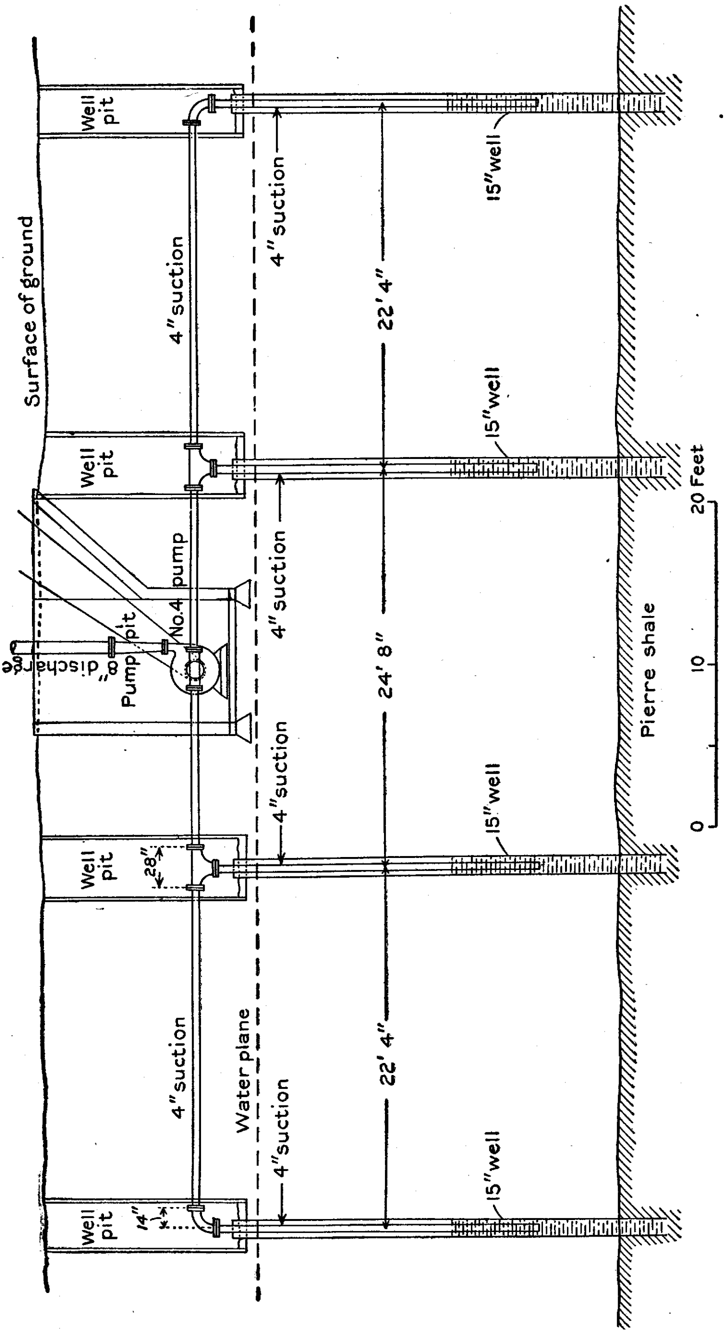


FIGURE 30.—Suggested arrangement of wells and pump designed to recover 400 gallons of water a minute.

proportion between the sizes of driving and driven pulleys, but both should be larger than those usually furnished with pumps and engines, say not less than a 12-inch pulley on a No. 4 pump.

The suction pipe on the pump and the discharge pipe should be large. A No. 4 centrifugal pump that draws water from a single well should have at least a 6-inch suction pipe, and the diameter of the discharge pipe should gradually increase from 4 inches at the discharge opening of the pump to 8 inches at a point 3 feet beyond the discharge opening and continue in this size to the flume or discharge conduit. Both the discharge and suction pipe should be galvanized spiral riveted No. 18 iron for 4-inch pipe and No. 16 iron for 6-inch pipe. The ends of the pipe should be provided with standard flanges for bolting together or for pipe fitting. Reducers of any size and length can be had or made to order. If three or more wells are connected to a No. 4 centrifugal pump the diameter of the part of the suction pipe that carries the water from a single well may be reduced to 4 inches.

A centrifugal pump loses its efficiency at once if it leaks air around the stuffing box or if there is an air leak at any place in the suction pipe. Many centrifugal pumps are now provided with a water seal around the stuffing gland that prevents leakage at that point.

A good centrifugal pump with inclosed impeller or runner should show an efficiency of about 60 per cent on a 30-foot lift. Single-stage centrifugal pumps, constructed with bronze impellers, made in two pieces so that the interior could be machined and smoothed, have shown an efficiency of about 80 per cent.

A large number of pumping plants are installed with foot valves at the bottom of the suction pipe. When these are provided a centrifugal pump is always ready to start after it is primed. The foot valves usually interfere very materially with the flow of water into the pipe, and it is undoubtedly more economical to omit them and place a flap valve at the upper end of the discharge pipe, which can be lowered when it is desired to start the pump. The foot valve is also undesirable in cold weather if the pump and suction pipe are above the frost line, as the pump and pipe may freeze if they are kept full of water. An ordinary cast-iron cistern pump connected to the top of the casing of the centrifugal pump can be used to prime the pump before starting.

The suction pipe usually installed by constructors of pumping plants is not only too small for the best results, but the elbows and tees used are very poorly adapted to the purpose intended. It is a common practice to use steam-pipe fittings for this purpose. In consequence the water is required to turn at sharp angles at the tees and elbows and the best results can not be obtained. In order to avoid this difficulty "long-sweep" fittings should be purchased. These are standard trade goods and can be obtained from any of the large dealers in pipe fittings. If an elbow or tee is used next to the pump, it should be of the flanged type and bolted directly to the pump. Figure 31 shows the difference in the two kinds of fittings.

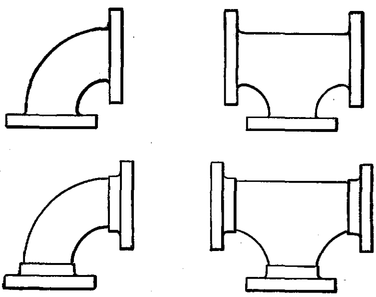


FIGURE 31.—Relative shape of standard and "long-sweep" pipe fittings.

ECONOMICAL LIFT.

It is very unlikely that it will pay to lift water under present conditions in the Republican Valley for a total distance of more than 30 feet, including the suction lift of the pump. If the pump lowers the water in the wells 10 feet, if the distance to water is 10 feet below the surface, if the discharge pipe is brought into a reservoir or flume 5 feet above the surface, and if 5 feet be added to cover loss of head due to friction in suction and discharge pipes, the total lift will be 30 feet. It will probably not pay to pump water to a greater height at any place in the valley, except for the irrigation of garden products and other high-priced crops.

ENGINES AND COST OF PUMPING.

If the total lift is 30 feet, if 450 gallons are pumped per minute, if the pump has an efficiency of 50 per cent, and if there is a loss of 10 per cent in the belt connecting the pump and engine, then it would require 7.6 horsepower to raise the water; that is, an 8-horse power engine would be large enough.

If possible the engine should be housed, or at least provided with a good canvas cover when not in use. Cotton waste should not be spared in keeping an engine clean, for a large amount of dust will be caught by accumulated grease, even when the engine is housed, and this will soon prove very injurious to the wearing parts.

A favorite engine for small pumping plants is the gasoline engine. Where the price of gasoline is high, it is very easy to make the cost of water prohibitive by the use of such power. Whether or not it pays to pump water by gasoline depends very largely not only on the distance the water must be lifted, but also on the kind of crop that is to be irrigated. Gasoline, even at a high price, is usually a cheaper fuel than coal in an ordinary steam engine of small horsepower. For plants requiring from 20 to 30 horsepower producer-gas generators can be installed, which will keep the cost of pumping down to a minimum. A suction gas producer, using anthracite pea coal for fuel, should furnish power at the rate of 1 horsepower per hour for each pound and a half of coal consumed. At $8 per ton the cost of coal should be equivalent to gasoline at 4 to 6 cents a gallon.

In large plants, requiring from 50 to 100 horsepower or more, a condensing Corliss engine is sufficiently economical where the cost of coal does not exceed $3.50 to $4 per ton.

The cost of recovering ground water from wells is made up of four principal items—(1) cost of fuel and supplies, (2) cost of labor, (3) charge for depreciation and repairs, and (4) interest on the first cost of the plant or the capital invested. The first and third of these items are partly under the control of the owner of the plant. If the plant is carefully designed and well proportioned and if all its parts are good, the cost of fuel can be kept at a minimum and the charge for repairs and depreciation will be low. The depreciation will be at least as great when the plant is idle as when it is running, especially if the machinery is then neglected and carelessly exposed. The charge for repairs and depreciation will be not less than 10 per cent of the first cost of the plant.

A small pumping plant will recover not more than 50 per cent of the power delivered to the belt by the engine. The loss in the belt amounts to 5 to 10 per cent, the loss in the pump amounts to about 30 per cent, and the friction losses in the suction and discharge pipes range from 5 to 20 per cent. In order to secure economy in running it is important that the engine should be large enough to do the work, but not too large. The use of gasoline engines whose capacity is largely in excess of the requirements of the work involves great loss.

Tests of several pumping plants in the Rio Grande valley are reported by Slichter, who publishes [a] a table giving cost of fuel, interest, and cost of labor estimated for each acre-foot of water recovered. Slichter also gives similar facts concerning the cost of pumping water by small pumping plants in the Arkansas River valley in western Kansas,[b] and describes a test of a producer-gas pumping plant at Rockyford, Colo.[c]

At almost any point in the river valleys of the western plains complete pumping plants, including wells, machinery, and buildings can be constructed for about $100 per horsepower required, and exceptionally the cost may be as low as $60 per horsepower.

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[a] Slichter, C. S., Observations on ground waters of Rio Grande valley: Water-Supply Paper U. S. Geol. Survey No. 141, 1905, p. 34.

[b] The underflow in Arkansas Valley in western Kansas: Water-Supply Paper U. S. Geol. Survey No. 153, 1906, p. 55.

[c] Idem, p. 82.

STORAGE RESERVOIRS.

In order to irrigate economically from a pumping plant it is usually desirable to pump the water into a reservoir having a capacity equal to the amount of water the plant can furnish in six to eight hours. Such a reservoir is absolutely necessary for the best results with small pumping plants. If the supply of water exceeds 500 gallons a minute it is possible to dispense with the reservoir. Plants furnishing over 1,000 gallons a minute can generally be best operated without a reservoir.

A reservoir should be well puddled to prevent leaking. The reservoir at the Richardson plant loses by seepage 1 inch in water depth every hour. If the area of a reservoir is 2,500 square feet, this seepage amounts to 15,000 cubic feet a day, or enough to cover an acre 4 inches deep.

LOSS BY EVAPORATION.

Water should be pumped as near as possible to the place at which it is to be used. Although it is cheaper to construct and operate a

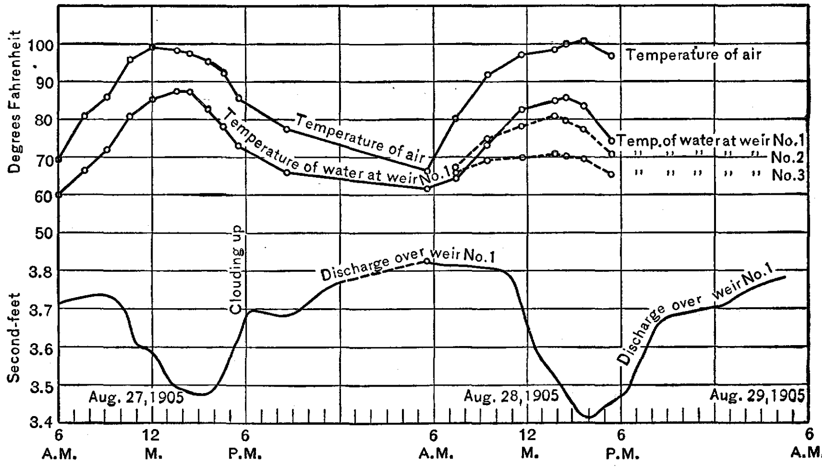

FIGURE 32.—Diagram showing loss by evaporation and vegetation on ditch 8,000 feet long near Ogalalla Nebr., August 27–28, 1905.

plant pumping 2,000 gallons than five smaller plants of the same combined capacity, the loss by evaporation and supplying plant growth along the ditch bank is considerable. In a ditch a mile long, carrying 4 cubic feet of water per second, this loss may be as great as 10 or 12 per cent during the warm hours of the day. Figure 32 shows the loss through evaporation and vegetation growing along the edges of a ditch 8,000 feet long. Each day there was a sudden drop in the discharge, beginning at about 9 a. m. and continuing until 4 p. m., after which the flow would increase very rapidly until 7 or 8 p. m. and remain comparatively constant during the night.

CONCLUSIONS.

The principal conclusions reached as a result of the investigation may be summarized as follows:

1. The source of the underflow is the precipitation in the drainage basin of the river.
2. The water-bearing gravel in the valley averages about 15 feet in thickness.
3. The water plane at St. Francis, Kans., slopes down the valley at the rate of 10.7 feet per mile.
4. The underflow of South Fork of Republican River moves at an average rate of 17 feet a day.
5. The rate of movement is, in general, much faster near the center of the valley than near its edges.
6. Better wells for irrigation can, in general, be sunk near the center of the valley than near its edges.
7. There is no danger that the underground water in the valley will be exhausted by pumping.
8. The water-bearing gravel contains enough large material to permit the use of a well strainer having openings as large as 1 inch long by three-sixteenths inch wide.
9. Except perhaps in a few localities along the northwestern side of the valley the quantity of dissolved salts in the ground water is not large enough to be injurious to plant life.

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