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HYDRAULICS OF WELLS

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OUTLINE

INTRODUCTION 1/

Although the subject of this lecture is supposed to be concerned primarily with the hydraulics of wells, Professor Weers has asked that I also discuss the effects that geological formations have on the quantity and quality of water available to wells. I will discuss first the geology of Colorado in relation to the availability and quality of water with particular reference to the most productive aquifers or water-bearing formations in the State. I will then discuss the hydraulics of wells with the aim of emphasizing the differences between water-table and artesian conditions.

GEOLOGIC CONTROL OF GROUND WATER

Ground water occurs in the pores or open spaces (interstices) in the rocks beneath the ground surface; hence, the movement, availability, and quality of ground water ~~is~~ are governed by the character and distribution of the rock formations--that is, by the geology. A highly permeable formation such as gravel or cavernous limestone will transmit water readily and may yield large quantities of water to wells; a formation of low permeability such as shale may contain large quantities of water in storage, but because the pore spaces are extremely small it transmits water very slowly and may yield little or no water to wells.

The occurrence of water is also governed by the attitude or dip of the rocks. A knowledge of the character and structure of the rock formations enables a trained geologist to predict approximate depths to potential aquifers or water-bearing formations.

On the following pages are described the availability and quality of ground water in the principal aquifers in Colorado.

1/ The writer has drawn freely from the many publications concerning the subject, particularly from Wenzel, L. K., 1942, and Bennison, E. W., 1947.

Availability

San Luis Valley.--The San Luis Valley is an intermountain basin that is underlain by stream-laid deposits such as sand, gravel, silt, and clay to depths of several thousand feet. The debris was carried into the valley by streams that head in the adjacent mountains--hence, all the beds of clay and of sand and gravel slope toward the low part of the basin which is on the eastern side of the valley. The deposits have been saturated with water to a point at or near ground surface with the result that ground water is available at shallow depths throughout almost the entire floor of the valley.

The layers of clay that are interbedded with the sand and gravel prevent the upward movement of water with the result that below a depth of about 100 feet the water is under sufficient artesian pressure to cause the wells to flow. There are now about 7,000 small-diameter flowing wells in the valley. In recent years, larger-diameter wells have been drilled to greater depths (nearly 2,000 feet) and have had natural flows of several hundred to several thousand gallons a minute (gpm). Large-diameter wells have also been drilled to shallower depths in the area north of Monte Vista. These wells do not have artesian flow but they are equipped with large-capacity pumps and yield large quantities of water for irrigation. It is estimated that in dry years nearly 500,000 acre-feet of ground water is discharged from wells in the San Luis Valley for irrigation.

South Platte Valley.--The South Platte Valley and its major tributaries are underlain by deposits of sand, gravel, and other stream-laid deposits. The stream-laid materials (called alluvium) underlie the flood plains and the lower terraces adjacent to the flood plains. The deposits range in thickness from a featheredge to nearly 200 feet and are saturated with water to a level about equal or slightly higher than the level of the water in the streams. In the flood plains, therefore, the water generally is only a few feet beneath the land surface whereas on the terraces it may be 25 to 50 or more feet beneath the land surface, depending upon the elevation of the terrace above the stream.

The alluvium in these valleys represent stream-laid sediments deposited in an old valley cut deeply into bedrock. During the period when the glaciers in the mountains were melting, large volumes of water were discharged into the plains area to the east. These tremendous streams cut deep valleys into the bedrock which consisted primarily of shale. The South Platte Valley, for example, was cut to a depth of nearly 600 feet. As the slope or gradients of the streams decreased, the streams could no longer carry their load of debris and they began filling the valley with sand and gravel. The South Platte Valley was filled to within 100 or 200 feet of the top with these materials and the flood plain was then at that high level. The gradient of the stream was then increased by uplift in the mountains or perhaps simply by climatic changes with the result that the stream again began to cut or erode. The stream removed much but not all of the upper part of the alluvium it had deposited previously. The remaining part now is the highest terrace in the valley. The stream developed new flood plains between periods of cutting until it has reached its present level. Each of the old flood plains is now marked by a terrace. Although a great deal of alluvium was removed by the stream, at least 200 feet of alluvium still remains in some places.

The thickness of the alluvium in the South Platte and tributary valleys ranges between wide limits. A well at one point may encounter the deepest part of the old buried channel and penetrate the maximum thickness of water-bearing materials; it may encounter a shallow part of the old valley and penetrate only a few feet of water-bearing materials. It is necessary, therefore, to undertake adequate preliminary test drilling before constructing a more costly large-diameter well.

Large-capacity wells for use in irrigation, by municipalities, and by industries, have been developed in the South Platte Valley and its tributaries--largely since 1930. It is estimated that there may now be as many as 5,000 large-capacity wells in the basin in Colorado, and it is further estimated that they may yield as much as 800,000 acre-feet of ground water annually.

Arkansas Valley.--The Arkansas Valley and its tributaries have a geologic history similar to that of the South Platte in that deep valleys were cut into the bedrock by streams, were largely filled with alluvium deposited by those streams, and were later eroded so that part of that alluvium was removed. The degree of later erosion was greater in the Arkansas Valley than it was in the South Platte Valley with the result that the maximum thickness of alluvium is about 125 feet in the Arkansas Valley compared to 200 feet in the South Platte.

The alluvium in the Arkansas Valley and its larger tributaries is saturated with water to a level about equal to that of the water in the stream channels with the result that large supplies of water are available to properly located and properly constructed wells. Owing to the differences in character and thickness of the water-bearing materials, adequate test drilling is essential to the proper location of the more expensive large-capacity wells.

Large-capacity wells have been drilled in many parts of the valley between Canon City and the State line. It is estimated that there are more than 1,000 large-capacity wells in the valley that discharge about 125,000 acre-feet of ground water a year. The water is used primarily for irrigation.

High Plains.--The High Plains in eastern Colorado is underlain by one of the most productive aquifers in the country. The High Plains extend from the Black Hills of South Dakota to the southern part of the Texas panhandle and includes parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas. The area is underlain primarily by the Ogallala formation which consists largely of stream-laid deposits such as sand, gravel, silt, and clay. The formation contains thick sections of saturated materials that yield large quantities of water to wells. In the Texas panhandle, for example, the aquifer is tapped by 25,000 large-capacity wells that discharge nearly 5,000,000 acre-feet of ground water annually for irrigation.

Although large quantities of ground water are available from wells in the Ogallala formation in the High Plains of eastern Colorado, the aquifer is essentially undeveloped. Supplies adequate for domestic and stock use are available at almost any place that is underlain by the Ogallala formation and large quantities are available to large-capacity wells in many areas where there are thick sections of water-bearing materials.

The formation ranges in thickness from a featheredge to about 500 feet in eastern Colorado and the depth to water is less than 50 feet beneath the land surface in a few places but commonly is 50 to 150 feet. In a few areas the depth to water exceeds 250 feet.

It is estimated that ~~there are~~ only about 200 large-capacity wells have been drilled in the High Plains of eastern Colorado and their annual discharge probably does not exceed 10,000 acre-feet.

Other Areas

The principal aquifers described above underlie only a comparatively small percent of the area of the State, but they yield more than 90 percent of all the ground water discharged by wells in Colorado. Throughout the remainder of Colorado the occurrences of ground water are as diverse as the geology. In the plains east of the mountains there are large areas underlain primarily by shale and supplies of water are difficult to obtain. In some of these areas, supplies can be obtained from deep-lying aquifers such as the Dakota sandstone. Where the aquifers lie at such great depth that it is not economically feasible to drill into them or ~~that~~ where the water in them is highly mineralized, it may be necessary to prospect for ground water in thin deposits of alluvium along small streams or arroyos. In prospecting for water along small streams, test holes should be drilled in a line across the valley (not up and down the valley) in order to locate the buried channel which commonly contains the thickest and most permeable water-bearing materials.

In the mountainous areas of Colorado, large supplies of ground water are difficult to obtain. Much of the area is underlain by dense hard rocks that yield little or no water to wells. Here again, prospecting should be concentrated along streams and draws in an attempt to locate water-bearing gravel or deposits of weathered bedrock.

Ground water in large quantities is also difficult to obtain on the western slope of Colorado. The deep canyons of southwestern Colorado have cut through the principal permeable formations with the result that most of the aquifers have been drained. Northwestern Colorado is largely underlain by thick sequences of shale and other rocks of low permeability, and supplies large enough for domestic and stock use are commonly difficult to obtain. Throughout much of the western slope the best areas to prospect for ground water are along streams where there may be thin deposits of alluvium that are water bearing.

Quality

San Luis Valley.--The quality of ground water in the San Luis Valley ranges between wide limits but the water is largely of the sodium bicarbonate type. The ground water in the Closed Basin north of the river moves toward the sump of the Closed

Basin which is marked by a series of lakes, one of which is San Luis Lake. The ground water along the edges of the Closed Basin is of excellent quality, but the quality deteriorates as the water moves toward the sump. The deterioration probably is caused largely by a concentration of salts through the processes of evaporation and transpiration but perhaps also by leaching of the soils with irrigation water. In the sump area the waters are so highly mineralized that they have very limited use.

South Platte Valley.--Ground water in the alluvium in the South Platte Valley generally is hard but is suitable for most uses. The principal constituents generally are calcium, magnesium, carbonate, and sulfate. Waters of this type and concentration generally need to be softened before being used for municipal supplies but many communities in the valley use the water without treatment--except for chlorination.

Ground water in alluvium in any valley generally is hard. The mineral constituents apparently are not usually dissolved from the sand and gravel in the alluvium but appear to come in part from minerals in the underlying bedrock. In the South Platte Valley, for example, the alluvium overlies the Pierre shale in much of eastern Colorado and, as the Pierre shale contains gypsum (calcium sulfate), the hardness may develop from the solution of gypsum in the underlying shale. In addition, ground water in alluvium generally lies at shallow depth with the result that the high concentration of mineral matter in the water may be in part the result of concentration by evaporation, transpiration, and leaching.

Arkansas Valley.--Ground water in the alluvium of the Arkansas Valley is very hard; in many places it cannot be used for domestic purposes. The water is only moderately hard at Canon City but the hardness increases rapidly to the east as the water moves through the alluvium over the shale bedrock which is in places highly gypsiferous. In western Kansas the underlying bedrock is the Ogallala formation which contains comparatively little soluble mineral matter with the result that the quality of the water in the alluvium improves in that reach of the valley.

Water in the alluvium of the Arkansas Valley in Colorado generally requires treatment to be satisfactory for domestic use, although it is used by some communities without treatment.

High Plains.--Ground water in the Ogallala formation in eastern Colorado is only moderately hard and is suitable for most uses. The depth to water is sufficient to prevent most concentration of mineral matter by evaporation or transpiration. The mineral matter consists primarily of calcium, magnesium, and carbonate. The water also generally contains sufficient fluoride to be beneficial to teeth but locally may contain enough (more than about 1.5 parts per million, Dean, 1936,) to cause mottling of the enamel of some children's teeth during the period of the formation of their permanent teeth.

None of the communities in the High Plains attempt to soften their water for domestic use although many homes are equipped with privately owned or rented water softeners. The average hardness of the ground water in the Ogallala formation is about 150 to 250 ppm (parts per million) or about 9 to 15 grains.

Dune-sand areas.--Special mention should be made of several geologic conditions that materially influence the quality of ground water. The most important of these is the effect of dune-sand areas on the quality of ground water. In those areas where dune sand overlies an aquifer such as alluvium or the Ogallala formation, the ground water in the underlying aquifer generally is relatively soft. The dune-sand areas generally have no outward surface drainage so that the runoff accumulates in depressions between dunes. Because of the high permeability of

THAD. I believe you will normally find F content slightly less also — perhaps 0.3 — 1.0 ppm? W.

the sandy soil the water moves downward rapidly to recharge the aquifer. Because of this rapid rate of recharge the water under the dune-sand area has not had a long period of time in which to dissolve mineral matter from the rocks.

An illustration of the effect of the dune-sand cover on the quality of water is the water-supply system at Brush, Colorado. The old supply obtained water from the alluvium in the city and had a hardness of 690 ppm (40.5 grains). At the suggestion of the U. S. Geological Survey, the city test-drilled an area in the sand hills south of the city and obtained a supply of soft water. Although the new wells tap the same aquifer only a few miles away, the water from the new wells has a hardness of only 70 ppm (4 grains.)

<u>Base exchange in bedrock formations</u>.--Many of the bedrock formations, such as certain sandstones, contain minerals that have a property that enables them to soften water--that is, they exchange sodium ions for calcium and magnesium ions so that although the concentration of mineral constituents is not decreased, the water is softened. The minerals are similar to those used in household water softeners. [substituting natural zeolites] Water in the Dakota sandstone generally is moderately hard in the areas of recharge but it commonly becomes progressively softer with depth even though the concentration of dissolved solids increases. Eventually, however, the water becomes so highly mineralized that it is unsuitable for most uses even though it is soft.

Excessive F in recharge areas in Dakota ss in N. Dak. Any problem in Colo.?

HYDRAULICS OF WELLS

Well-Versus Aquifer Performance

There is considerable confusion about the difference between well performance and aquifer performance. Wells are engineering structures which, if designed and built in accordance with the theoretical considerations governing their performance, should yield the maximum amount of water with the least drawdown. Aquifers are rock formations that store and transmit water; the quantity of water stored and the rate the water is transmitted are hydraulic properties of the aquifer.

Although both wells and aquifers have separate characteristics, they must be considered together in the proper development of ground-water supplies. The hydraulic characteristics of the aquifer determine the type and spacing of wells required for the most efficient withdrawal of water.

Water-Table Wells

The term "water-table wells" refers to those wells that obtain water from aquifers in which the water is not under artesian pressure. This includes most of the large-capacity wells in the State such as the shallow wells in the San Luis Valley, and the deeper wells in the High Plains. When water is encountered in the drilling of these wells it does not rise appreciably above the level at which it is encountered. The performance of a water-table well is considerably different than the performance of an artesian well--hence, the two types are discussed separately.

Drawdown.--It is common to hear the statement that a certain well has a large discharge but no drawdown. [Drawdown is the vertical distance between the static (pre-pumping) water level and the pumping water level.] Such a statement is false because water cannot be taken from a well without ~~a~~ drawdown. When water is withdrawn from a well the water level declines in the well. This creates a hydraulic gradient or slope in the water table toward the well from all directions and water moves toward the well. The water cannot move into the well unless there is a gradient toward the well and there can be no gradient until there is a drawdown.

Cone of depression.--As soon as a pump begins discharging water from a water-table well, the water level is lowered in and around the well. The water table assumes a form comparable to an inverted cone, although it is not a true cone. Where the water-bearing material is homogeneous (uniform in grading or size) the cone of depression will be circular if the initial or static water table is horizontal but somewhat elliptical if the initial water table has a slope. Some water-bearing material will be unwatered by the decline of the water table, and the water drained from this material will percolate to the pumped well. Thus, for a short time after pumping begins, most of the water that is pumped from a well comes from the unwatered sediments comparatively close to the pumped well, and temporarily very little water may be drawn to the well from greater distances. However, as pumping continues, a hydraulic gradient that is essentially an equilibrium or stable gradient will be established close to the pumped well, and water will be transmitted to the well through the water-bearing material in approximately the amount that is being pumped.

The decline of the water table and the resultant unwatering of material in this area will then be much slower. This necessitates the percolation of more water from greater distances and the cone of depression will expand, gradually draining material at greater distances. Thus, as the pumping of the well continues, more of the formation will gradually be unwatered and an appreciable drawdown will be noted farther from the well. Inasmuch as an equilibrium gradient can be established at increasing distances from the pumped well only by an increase in drawdown, the water table near the pumped well, in order to maintain an approximate equilibrium, will continue to lower indefinitely, but at a decreasing rate. If no water is added to the formation the water table will continue to decline, so long as the well is pumped, and the cone of depression will eventually extend to the limits of the formation. Recharge to the formation may, however, halt the development of the cone of depression by furnishing additional water, which will become a supply for the pumped well.

After the discharge of a well is stopped, water continues to percolate toward the well under the hydraulic gradient set up during the period that the well was discharging, but instead of being discharged by the well it refills the well and the interstices or the open spaces in the material that were unwatered. As the formation near the well is gradually refilled, the hydraulic gradient toward the well is decreased and the recovery becomes progressively slower. At distances comparatively far from the well the water level may continue to lower for a considerable time after the discharge ceases because at those distances water still is taken from the interstices of the material to supply the water that refills the sediments ~~around~~ nearer the well. In time there is a general equalization of water levels over the entire region, and the water table will assume a form similar to that which it had under the initial conditions, although it may remain temporarily or permanently somewhat lower than before pumping began.

The normal development of the cone of depression in water-table wells may be altered by several factors such as the presence of a nearby stream, fault, or shale barrier. The cone of depression will extend outward from the well at ever increasing distances. If it reaches a stream it will become stabilized in that direction and water will move from the stream to the well. If the cone of depression reaches a fault or shale barrier, it can extend no farther and the drawdown in the well will increase.

It is common practice to test large-capacity wells for periods ranging from a few hours to about a day. Where the aquifer is extensive this may be long enough but where there are relatively impermeable materials nearby a 1-day test may not be long enough to reveal the effect of such materials and failure to recognize this may cause serious consequences. A well drilled recently in a small valley in Colorado was pumped for 24 hours at the rate of 720 gpm with a drawdown of 12 feet. Several other wells of similar capacity were drilled and tested in a similar manner. On the basis of these short tests, the pumps, a booster station, and a long pipeline were designed and purchased and the wells were put into operation. The well field is in a narrow valley and the shale wall of the buried channel rises above the water table within a few hundred feet of the wells. After 26 days of pumping the one well was discharging only 600 gpm with a drawdown of about 20 feet. The specific capacity of the well (discharge per foot of drawdown) had declined from 60 to 30. The specific capacity of the other wells declined a similar amount. By neglecting to test the wells for a longer period the plant was overdesigned at a cost of many thousand dollars.

Specific capacity.--The specific capacity of a well may be defined as its rate of discharge in gallons a minute per foot of drawdown--that is, if a well discharges 1,000 gpm with a drawdown of 10 feet it has a specific capacity of 1,000/10=100. Specific capacity is a useful unit for comparing the capabilities of wells and the productivity of the aquifers. In Huerfano County, for example, there are two large-capacity wells, one discharges 1,200 gpm and the other 400 gpm. It would appear that the larger well is in the most productive aquifer, but it has a drawdown of about 400 feet and has a specific capacity of only 3 gpm per foot of drawdown. The smaller well has a drawdown of only 20 feet and its specific capacity is 20. Specific capacity is also useful in determining the condition of a well. If the specific capacity of a well declines over a period of years even though the water table has not declined, then we know that for some reason the water is not entering the well as freely as before. This may be caused by encrustation of the well screen, by sanding, or by other factors. If the specific capacity increases even though the water table has not risen, then we know that water is entering the well more freely. This commonly happens during the development of a well when the fine particles are drawn into the well and pumped out leaving a natural gravel pack around the well.

Relation of drawdown to discharge.--It is commonly believed that the discharge of a well increases in direct proportion to the increase in drawdown--that is, it is believed that if a water-table well yields 100 gpm with a 10-foot drawdown it will yield 200 gpm with a 20-foot drawdown. According to Bennison (1947, p. 209) the discharge of a well does not have a straight-line relation to the drawdown. In a table prepared by Bennison (shown below) are shown the percentages of the total potential discharges that theoretically are obtained for various percentages of drawdown. The table shows, for example, that with 50 percent of the total drawdown a well will discharge 76 percent of its total capacity. This means that if a well penetrates 100 feet of water-bearing gravel and its theoretical maximum yield with 100 feet of drawdown is 1,000 gpm, the well will yield 760 gpm when the drawdown is 50 feet instead of 100 feet. Similarly, the table shows that if the well is pumped with a drawdown of 70 feet (70 percent of total) it will yield 92 percent of its total capacity or 920 gpm. Obviously the data in the table are not reliable in the upper range of drawdowns, for in order to obtain 100 percent of the yield the table shows that the drawdown must be 100 percent. If the drawdown is 100 percent the water level will be at the bottom of the aquifer, no water could get into the well, and the discharge would be zero. Except for the breakdown in the uppermost range, however, the table has proved to be reliable and very useful.

The table illustrates graphically the inadvisability of lowering the water level of a well to the bottom of the hole unless it is necessary to obtain a required amount of water. If a municipal well, for example, penetrates 100 feet of water-bearing gravel, has a static water level 10 feet below ground surface, and discharges 1,000 gpm with a drawdown of 100 feet, the total lift will be 110 feet. As in the case of many communities, this well may be much larger than they need and, if so, it would be a sizeable saving in power if the well were pumped at a rate of about 750 gpm. The drawdown would be nearly 50 feet and the total lift would be about half as great as it is when pumped at the rate of 1,000 gpm. In other words, it will save money to pump the well at a slower rate for a longer period of time.

Relation of drawdown to discharge

Percent of total drawdown	Percent of total yield	Percent of total drawdown	Percent of total yield
10	18	60	85
20	35	70	92
30	51	80	96
40	64	90	99
50	76	100	100

Relation of diameter to discharge.--The discharge of a well increases when the diameter of the well is increased but not, as commonly believed, in direct proportion to the increase in diameter. A well should be large enough to accommodate the pumping equipment with ease but the days of the large 20- and 40-foot diameter wells are gone--except perhaps in specialized cases. As shown in the list below (reproduced from Bennison, 1947, p. 208), other factors being equal, increasing the diameter of a well from 2 inches to 4 inches will increase the yield by only 10 percent and increasing it to 48 inches will increase the yield only 55 percent.

Increase in yield caused by increase in diameter

Well diameters (in inches)								
2	4	6	8	12	18	24	36	48
Increase in yield (in percent)								
0	10	15	20	25	33	38	48	55
	0	5	10	15	23	28	38	45
		0	5	10	18	23	33	40
			0	5	13	18	28	35
				0	8	13	23	30
					0	5	15	22
						0	10	17
							0	7

Well spacing and interference.--Well spacing is a problem commonly encountered in the development of ground-water supplies. Wells should generally be spaced far enough apart that serious mutual interferences and the resultant increases in drawdowns and decreases in yields are held at a minimum. Proper spacing of wells will permit the development of the most water with the least lift.

The proper spacing of wells is governed largely by the hydrologic characteristics of the aquifer--generally, the more permeable the aquifer the less space required between wells. In a highly permeable gravel the spacing may need to be only a few hundred feet, whereas in materials of low permeability the spacing may need to be several thousand feet. In one well installation, eight wells were drilled in a line with a spacing of 250 feet between wells with the result that there was serious interference between wells. The eight wells had a combined discharge of 3,500 gpm. By abandoning every other well and resetting the pumps the interference was minimized and the discharge was increased to 4,500 gpm with the same lift.

A similar experiment was made with a battery of four wells in the Arkansas Valley in western Kansas. The wells were 56, 92, and 73 feet apart. When pumped separately they discharged a total of 3,035 gpm but when pumped together they discharged only 2,325 gpm. There was no interference between the outer wells which were 221 feet apart, but the interference between the two closest wells (56 feet apart) was sufficient to reduce their discharge from 1,494 to 1,281 gpm or about 14 percent (McCall and Davison, 1939, table 4).

As the extent of the cone of depression is dependent upon the permeability of the aquifer (other things being equal), a knowledge of the hydrologic properties of the aquifer are essential to proper well spacing. Under ordinary conditions, competent well drillers have learned from experience about what spacing is required for a particular aquifer. In unknown territory it may be necessary to run pumping tests and make engineering calculations to predict the extent of the cone of depression after a given period of pumping.

Penetration of aquifer.--There is an old saying that "the deeper the well, the better." This statement is generally true in that so long as additional water-bearing materials are encountered, the deeper the well is drilled into these materials the more water the well will produce with a given drawdown. In a uniform gravel, for example, a well that penetrates 100 feet below the water table will produce almost twice as much water as one that penetrates only 50 feet below the water table.

This important principle is commonly overlooked or is avoided for economy--and false economy at that! The owner of a large-capacity well may save several hundred dollars by not drilling the last 50 or 100 feet to the bottom of the aquifer, but he may pay that "several hundred dollars" many times in additional power costs during the life of the well. In the High Plains of western Kansas, for example, the deep irrigation wells commonly penetrate only about 150 to 200 feet of the water-bearing materials in the Ogallala formation. The casings generally are seated in a layer of clay and the wells generally discharge about

1,000 gpm with an average drawdown of about 75 feet. A well completed recently in that area was drilled to the bottom of the formation and penetrated about 400 feet of water-bearing materials. The well has a discharge of 3,400 gpm with a drawdown of 14 feet. The well will discharge 1,000 gpm, like the other wells, with a drawdown of less than 5 feet. The other wells, throughout their life, will lift all the water 70 feet farther than the new well. Inasmuch as the average well in that area pumps several hundred acre-feet of water a year, the new well will save more than $500 annually in cost of pumping.

Artesian Wells

Artesian wells are those in which the water rises in the well above the level at which the water is encountered--that is, the water is under pressure or head. If the water rises above the level of the ground surface and flows, it is called a flowing well. The "head" of a well has been defined as the level to which water will rise in a tightly cased well that has no discharge. In other words, if an artesian well has a head of 50 feet above ground surface and the casing is extended 50 feet above the ground, the water will rise to the top of the extended casing but will not flow over the top.

Artesian wells are similar to water-table wells in some respects, but in others they are very different. Although artesian wells have been drilled in many parts of Colorado, more than 90 percent of the flowing wells in the State are in the San Luis Valley. The geology of the valley is ideal for the development of artesian wells. The alternating layers of clay and of sand and gravel that underlie the valley were deposited by streams carrying debris from the mountains along the sides of the valley. As the gradient or slope of the streams was toward the low point of the basin, the layers of clay and of sand and gravel also slope from the sides toward the low part of the basin. Water that enters the layers of sand and gravel along the sides of the valley moves toward the center of the valley between the layers of clay. As the layers of clay are relatively impermeable and will permit little upward or downward movement of the water, the water is under artesian pressure. When a well is drilled through the capping layer of clay, the pressure is released and water rises in the well.

There are a great many artesian aquifers in the San Luis Valley, but it is likely that many of them are interconnected. The alternating layers of clay and of sand and gravel extend to depths as great as 1 mile. An oil test drilled to a depth of 6,024 feet encountered hundreds of artesian strata in the first 5,000 feet. A well drilled to a depth of 1,000 feet on the Baca Grant penetrated more than 70 artesian sands; in 55 of these sands the water was under sufficient head to flow at the ground surface.

Drawdown.--An artesian well acts much like a water-table well when water is discharged, although there is some difference. An artesian aquifer does not have a water table, as such. The aquifer is completely filled with water under pressure. When a well penetrates the aquifer the water rises in the well to a point above the top of the aquifer. The height that the water rises in a tightly cased well that has no discharge is commonly referred to as the pressure head. In areas of artesian flow it generally is expressed in terms of feet above land surface or above some fixed point such as the top of the casing. The piezometric surface of any artesian aquifer is an imaginary surface that everywhere coincides with the head of the water in the aquifer. The piezometric surface is comparable to the water table in that it is not a level surface but slopes in the direction of movement of the water. When a well is pumped, a drawdown and cone of depression result. Although this cone is imaginary in that is is merely a lowering of pressure or head rather than a lowering of the water level, it is just as real as in a water-table well in its influence on the hydraulics of wells. When an artesian well flows or is pumped, the resulting drawdown is indicated by a lowering of the head above ground surface if the well flows or a lowering of the water level in the well if it is pumped.

Cone of depression.--As soon as artesian wells begin discharging, a cone of depression is developed in the piezometric surface even though the entire cone may be above the ground and water moves toward the well from all directions. The cone of depression develops in a manner very similar to that of a cone developed under water-table conditions. However, water is not removed from storage by the unwatering of a part of the formation but by the compaction of the aquifer and expansion of the water upon the release of pressure when the head is reduced. Whether the compaction of the aquifer and associated beds is strictly proportional to the decline in pressure is not known, but probably the compaction increases with the decline in pressure, and thus the compaction is greatest near the discharging well. Hence, the quantity of water squeezed out of the formation is greatest near the well. The squeezing out of water from the formation by compaction delays the development of the cone of depression in much the same way that the development of the cone of depression for water-table conditions is delayed by the unwatering of part of the formation. However, the quantity of water removed from an artesian aquifer by compaction is ~~in most instances~~ much less than the quantity of water removed by the unwatering of a part of a formation, and the drawdown of the piezometric surface and development of the cone of depression under artesian conditions ~~usually~~ is more rapid than under water-table conditions.

Both are from storage ADA

There is a distinct difference between the removal of water ~~from storage~~ from artesian aquifers by compaction and the removal of water from a water-table aquifer by the unwatering of part of the formation. ~~The specific yield (ratio of the volume of water that an aquifer will yield by gravity to its own volume) of the formation is not related to the thickness of the formation, hence, lowering of the water table a given amount will release the same quantity of water to the pumped well regardless of the thickness of the formation. On the other hand,~~ However when a water-table well is pumped, the principal source of water is the water that drains by gravity from within the cone of depression although some water is released by compaction of the saturated portion of the aquifer because of the decrease in pressure. The amount of water obtained by gravity drainage is from several hundred to several thousand times the amount of water released by compaction so that the thickness of the aquifer [illegible] the amount of compaction of an aquifer and associated beds depends on their thickness, and, hence, a lowering of the water level a given amount in a well discharging from an artesian aquifer will release more water to the well if the beds are thick than if they are thin.

Specific capacity.--The specific capacity of a well has been defined in the section on "Water-Table Wells." The specific capacity of an artesian well generally is less than that of a water-table well. Inasmuch as water is discharged from an artesian well by compaction of the aquifer rather than by unwatering the aquifer, drawdowns in artesian wells generally are greater and specific capacities, therefore, are less. Water-table wells in alluvium in Colorado commonly have specific capacities of 50 to 200 gpm per foot of drawdown whereas many artesian wells such as those in Denver and in the Arkansas Valley commonly have specific capacities of less than 1 to seldom more than 10 gpm per foot of drawdown.

Relation of drawdown to discharge.--As pointed out above, a water-table well will discharge 76 percent of its total capacity at only 50 percent of its total possible drawdown and in that instance the common belief that discharge is directly proportional to drawdown is false. In artesian wells, however, the discharge is nearly proportional to the drawdown. A drawdown of 50 percent, for example, will produce 55 percent of the total capacity. Listed below are the relations between drawdown and discharge in an artesian well (Bennison, 1947, p. 209). These data also break down in the upper ranges for the reasons given on p. 14.

Relation of drawdown to discharge

Percent of total drawdown	Percent of total yield	Percent of total drawdown	Percent of total yield
10	13	60	65
20	25	70	74
30	36	80	83
40	46	90	92
50	55	100	100

Well spacing and interference.--Although well spacing and interference were discussed extensively in the section on water-table wells it should be particularly emphasized for artesian wells. The cone of depression under water-table conditions expands slowly by the process of unwatering the aquifer and it may take a long period of time for the unwatered materials to drain completely. In an artesian aquifer the cone of depression expands rapidly. As in a closed hydraulic system, a release of pressure at one point may be noted at great distances in a very short time. In the South Platte Valley, for example, it generally requires days or weeks of pumping for the cone of depression around an irrigation well to extend several hundred to several thousand feet from the well. In one locality in the South Platte Valley, however, the water is under artesian pressure because of an extensive layer of clay in the alluvium. When one well in that area is pumped, the water level in another well 1 mile away will decline more than 2 feet in less than 2 minutes. In the artesian areas of the Atlantic Coastal plain, the cone of depression around a discharging artesian well has been found to extend more than 20 miles from the well and undoubtedly extends farther. Under these conditions, adequate well spacing may become impracticable and wells may have to be spaced in such a manner not to avoid interference but to keep interference at a minimum. We are faced with just this problem in the Denver area at the present time. The water level in an artesian well in southwest Denver has declined 52 feet since 1948. In all that time, however, the well has discharged no water and the nearest well tapping the same aquifer is more than a mile away. The water level is being lowered by other wells more than a mile away. It is likely that a few widely spaced wells in this aquifer in the Denver metropolitan area would lower the water level throughout the area.

Summary

1. The availability and quality of ground water is controlled by geology, and a knowledge of the geology of an area aids materially in the proper development of ground-water supplies.

2. Aquifers are either water table or artesian and wells tapping the two types of aquifers have different hydrologic characteristics.

3. Water-table wells differ from artesian wells in that their discharge does not have as close a relation to the drawdown; and they generally have lesser drawdowns, smaller cones of depression, and smaller specific capacities.

4. All wells should be properly spaced in order to keep interference between wells at a minimum.

5. The discharge of a well is increased very little by increasing the diameter, but it is increased appreciably by increasing the depth through water-bearing materials.

References

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