GROUND-WATER DESIGNS AND PATTERNS

BY

J. W. STEWART

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J. W. Stewart[2]

INTRODUCTION

In our everyday life we observe without a second thought a multitude of symmetrical and repetitive patterns of Nature's wonders. We see her work in a thousand different ways — the geometrical pattern of a snowflake, the streamlined shape of a raindrop, the symmetry of a crystal, the spiral of a sea shell. All around us Nature is unceasingly at work creating an infinite variety of designs and patterns.

We know that nearly everything on earth is a repetition of what has happened before because Nature is a great repeater. We can expect the oak leaves to be green in spring and summer and multicolored in autumn, the watermelon to grow from a watermelon seed, and the peach tree to bear peaches. We do not need a weatherman to tell us that air temperatures begin to rise in the spring, reach their maximum in summer, and then decline in fall and winter. The cyclic pattern of warm and cold air is repeated yearly, and a simple graph of temperature versus time would show the changes in temperature that occur seasonally. From experience we know that the seasonal temperatures vary from year to year. Nevertheless the basic cyclic graph would be essentially unchanged if it were extended to include several years of records.

In a similar manner we could show graphs of rainfall, humidity, ocean tides, lake levels, river discharges, ground-water fluctuations, and many other common natural phenomena which either directly or indirectly affect our daily lives.

This paper is concerned with cyclic and noncyclic fluctuations of the water table within the earth's crust as recorded by instruments installed at wells. Several graphs are included to show the many different types of water level fluctuations which we can expect to appear on the records. In order to properly interpret and evaluate the records we must recognize the various factors which influence the ground water table.

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1 Publication authorized by the Director, U. S. Geological Survey.

2 Hydraulic Engineer, U. S. Geological Survey, Tampa, Florida.

The purpose of this article is twofold: first, to show the principal types of ground water patterns produced by the ever changing water level within the earth's crust; and second, to show how man has changed nature's simple basic ground water designs into somewhat complex but symmetrical and harmonious patterns. No attempt is made to discuss in detail the basic principles governing the various types of natural water level fluctuations, and for this reason only a brief discussion of the causes of the fluctuations is given in this article. Several excellent papers are listed in the references for those who wish to read more about the subject.

As an introduction to the many different types of designs and patterns produced by the changing water table as a result of natural and man-made causes, several simple graphs which show a minimum of fluctuations and several complex graphs which show a wide variety and range of fluctuations are included.

FLUCTUATIONS CAUSED BY RECHARGE AND DISCHARGE

The simplest water-level graph is one obtained during periods when the ground-water reservoir is filled to a level such that the water remains fairly steady and shows a minimum of fluctuations, or it is slowly rising during a wet period or slowly declining during a dry period. Such graphs are typical of those obtained from dug and drilled wells throughout Georgia. The graphs are relatively simple and easy to understand because they show a minimum of patterns and designs, and in a way are no different from most every-day graphs with which we are familiar. For example, Figure 1 is a graph which shows the water level declining in a shallow dug well near Savannah, Georgia, during late summer when the weather was hot and dry and no rain had fallen for several days. As noted on the first part of the graph, the water level in the well was steadily declining and the downward trend continued until interrupted by rain water which seeped to the saturated zone, and the deficiency of the preceding dry period was partially made up. As water seeped into the formation it began to fill up the pore spaces and caused a temporary reversal in the downward trend of the water table. However, because of the relatively light rainfall and the high evaporation losses, the amount of water reaching the ground-water zone was insufficient to make up for the deficiency of the previous rainless period. Consequently, after the intitial rise the water level continued about the same downward trend as was noted before the rain. The declining trend generally continues until the coming of winter and spring rains when the water

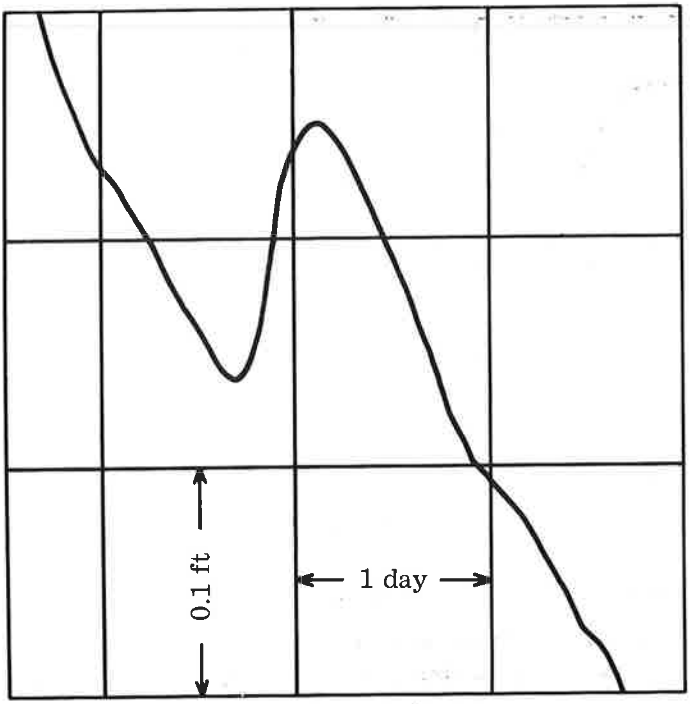


Figure 1. The decline of the water level in a dug well during a dry period, and the rise of the water level following a rain.

table begins a steady rise, which will continue until the beginning of a new growing season.

FLUCTUATIONS CAUSED BY TRANSPIRATION AND EVAPORATION

Plants need water to grow, otherwise they wither and die — a simple but basic fact of life with which we all are familiar. Few people are aware of the varied conditions under which plant life exists and the extent to which Nature has provided plants a means of sustaining growth. For example, in parts of the arid areas of the western United States plant roots have been found to extend as much as a hundred feet or more into the soil and rocks seeking much-needed water to grow and live. Such cases are not uncommon in arid areas where the rainfall is only a few inches a year and the water table is fairly deep. However, in Georgia where the average annual rainfall is about 50 inches a year and the water table in most places is near land surface, it is highly unlikely that plant roots would need to

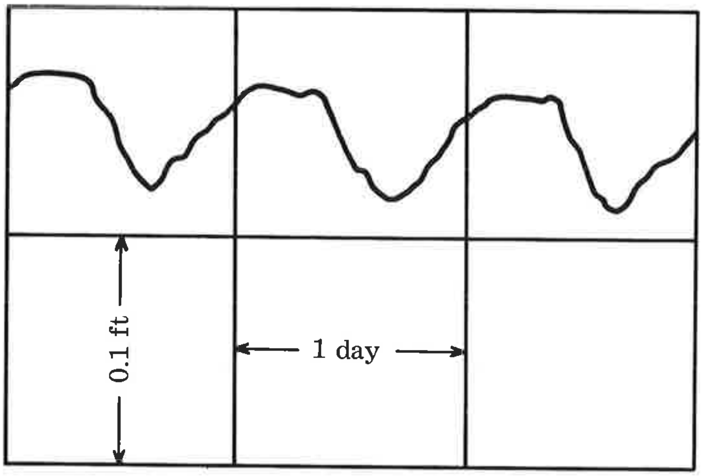


Figure 2. Water-level fluctuations caused by transpiration of water by plants.

extend such great distances into the earth. Therefore, in many parts of the state where the water table is less than about 10 to 15 feet below the surface the roots of many plants, especially those of trees, have penetrated the saturated zone in order to insure adequate water during the growing season.

Figure 2 is a graph showing the use of ground water by vegetation in a heavily wooded area of oak, hickory, pine, and gum trees in Dawson County, Georgia. The water table was about 6 feet below land surface. The pattern is produced by the process called transpiration (the evaporation of water vapor from the surface of green tissues in plants), and shows a marked daily fluctuation of the water table. The water level declines during the day when transpiration is greatest, and rises during late evening and night when transpiration is least. For the well shown the water level begins to decline about 8 to 9 a.m. and reaches its lowest level at 4 to 5 p.m., at which time the water begins a rise which continues until 3 to 4 a.m. the next day, then levels off at about 8 a.m., just prior to repeating the cycle again. As a rule the daily drawdown is somewhat greater than the nightly recovery, the deficiency in recovery indicating the decline of the water table.

FLUCTUATIONS CAUSED BY VARYING PRESSURE LOADS

Atmospheric Pressure

Figure 3 shows the water level in a well affected by changes in atmospheric pressure. We know from the work of previous investigators that the water level in some wells rises when the pressure decreases, and the water level declines when the pressure increases. That is to say, when the atmospheric pressure increases, the pressure exerted on the free water surface in a well is greater than that on the aquifer, and the net result is a decline in the water level in the well. The reverse occurs when the atmospheric pressure decreases. Thus, the changes in atmospheric pressure produce a systematic pattern of daily high and low water levels, and the magnitude and occurrence of the fluctuations depend upon weather conditions. In Figure 3 the graph shows two daily highs and two daily lows, the highs occuring shortly after midnight and in the afternoon (the vertical lines represent midnight), and the lows occurring shortly before noon and shortly before midnight. The water level in most artesian wells in Georgia is affected by change in atmospheric pressure.

Wind

Wind gusts may cause the water level in wells to fluctuate, however, such fluctuations are small and seldom exceed half an inch, depending upon the direction and speed of the wind. The solid segments of the graph in Figure 4 were caused by variations in the direction and speed of the wind blowing across the shelter housing the recording instrument. Such fluctuations are sporadic and occur only when wind conditions are favorable. Peak gusts, which produce large and very rapid pressure changes within the shelter and well

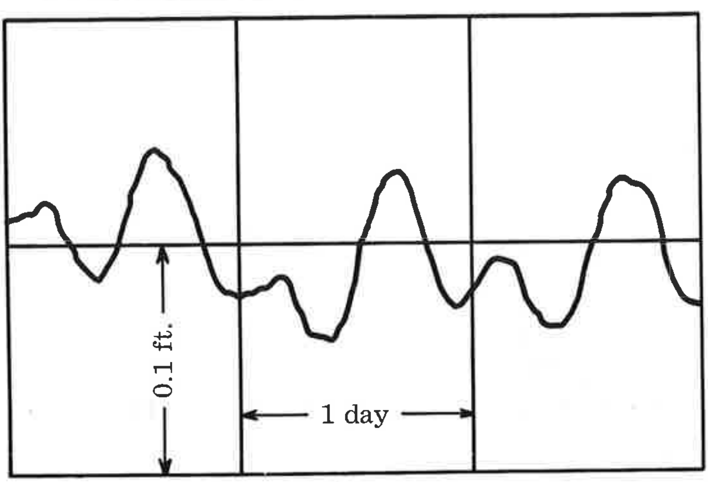


Figure 3. Water-level fluctuations caused by changes in atmospheric pressure.

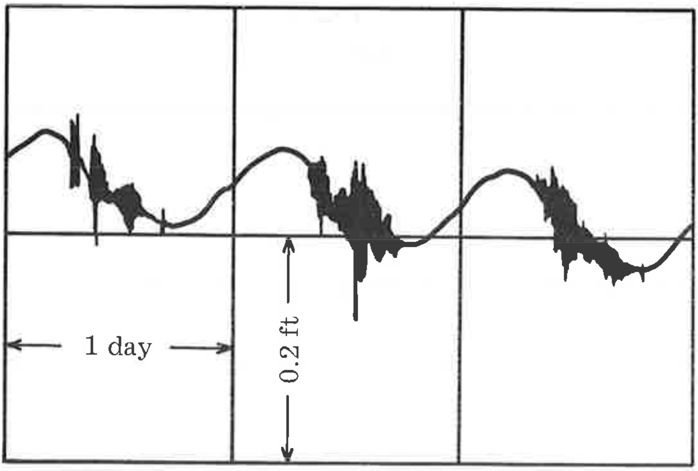


Figure 4. Water-level fluctuations caused by changes in wind speed.

casing, cause the jagged and irregular traces on the charts. The graph in Figure 4 differs from the preceding ones in that the solid areas covered by wind at irregular intervals add an additional pattern to a simple graph.

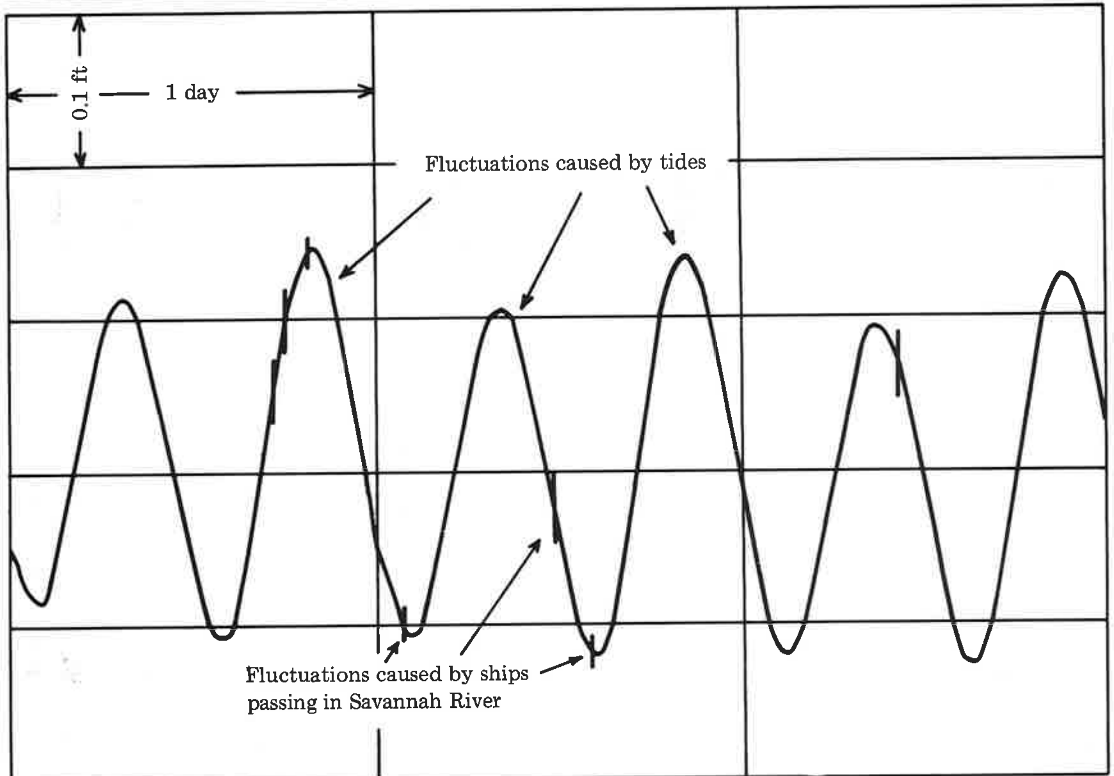
Ships

An interesting and unusual water-level fluctuation in an artesian well, caused by ships in the Savannah River, was reported by Odom (1961, p. 28-29). He attributed the fluctuations in the well to the energy of the ship's motion as it passes the well. The well is about 800 feet from the center of the Savannah River ship channel, and the water level in the well is affected by both ocean tides and passing ships. Figure 5 shows the water level in the well during a 3-day period in September 1959. The large cyclic fluctuations are due to tidal loading and the small straight-line variations superimposed on the cyclic graph are caused by ships passing the well in the adjacent Savannah River. The fluctuations are small and range from 0.1 to 0.3 foot, the magnitude depending upon the size and speed of the ships.

The straight-line fluctuations caused by passing ships add very little design or pattern to the cyclic graph caused by tidal loading, and as a result the graph is similar to the one shown in Figure 9.

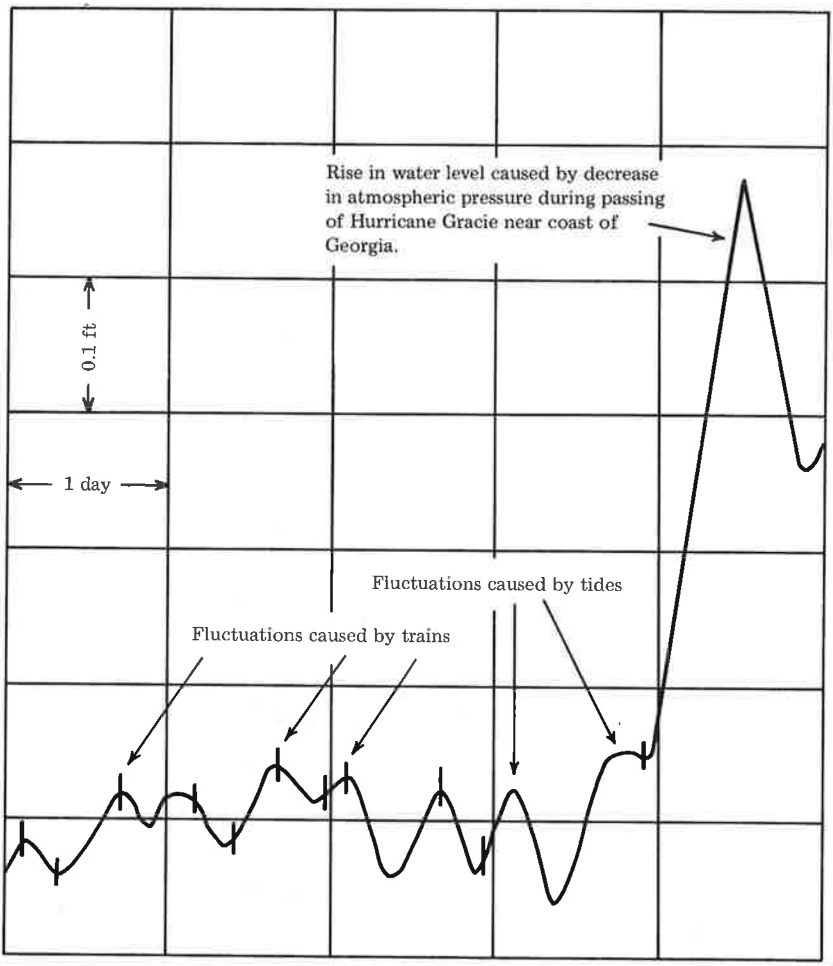
Trains

The effects of passing trains on the water level in a 431-foot artesian well in Effingham County was described by Odom (1961,



After O. B. Odom, 1961

Figure 5. Water-level fluctuations caused by tides and passing ships.



After O. B. Odom, 1961

Figure 6. Water-level fluctuations caused by passing trains, tides, and a hurricane.

p. 29). The short vertical line shown on Figure 6 represents sudden rises and declines of the water level in the well as nearby trains passed the well. The fluctuations are caused by the compressional effect of the weight of the trains on the elastic aquifer in much the same manner as passing ships cause the water level to change. The water level rises as the train approaches the well, and reaches its peak about the time the train is opposite the well; then, as the train passes by, the water level declines to its minimum level and slowly recovers to its initial position. It was found that the magnitude of the fluctuations varied according to the length, weight, and speed of the passing trains. Long, heavy, slow-moving trains caused the largest fluctuations and short, light, fast-moving trains caused the smallest ones.

Water-level fluctuations caused by passing trains are very small and seldom exceed 3 or 4 inches. Thus, the additional fluctuations which are registered as short ticks on the graph do not change the general pattern and trend of the water level in the well.

The significance of the fluctuations caused by trains, as well as those caused by ocean tides and atmospheric pressure, indicates that the artesian aquifer is elastic. That is, the limestone in which the

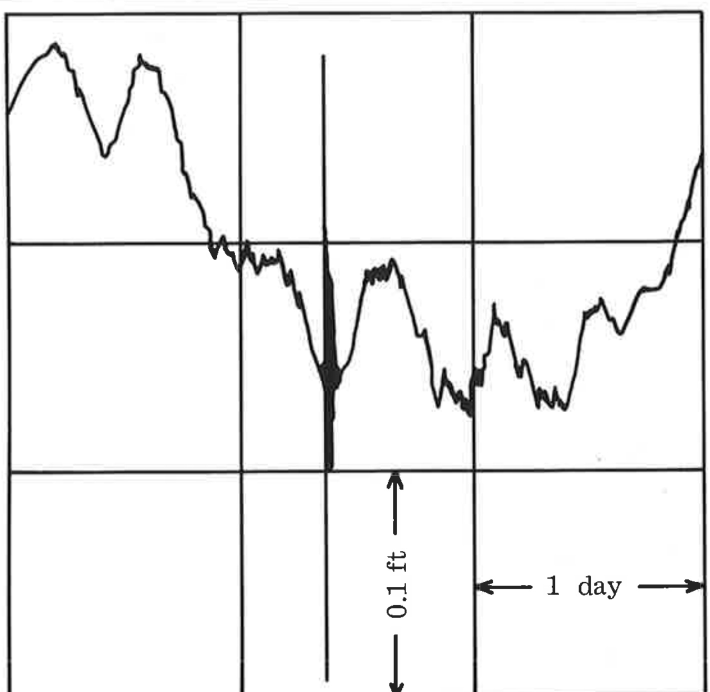


Figure 7. Water-level fluctuation in a Georgia well caused by an earthquake occurring in Mexico.

water occurs is not rigid and unbending but will be compressed if a sufficiently heavy load is applied, and will expand when the load is removed.

Hurricanes

Water-level fluctuations caused by hurricanes are due to changes in atmospheric pressure as described briefly on page 3. Figure 6 shows the rise in water level caused by the passing of Hurricane Gracie near the coast of Georgia on September 28-29, 1959 (Odom, 1961, p. 29). The large decrease in atmospheric pressure which accompanied the hurricane caused the water level in the well to rise about a foot. The highest water level in the well and the lowest atmospheric pressure in the area occurred shortly before noon on September 29, which is about the same time the center or "eye" of the hurricane passed closest to Savannah.

The pattern of the water-level fluctuations during the period of the hurricane shows a marked difference as contrasted to that obtained for the typical diurnal fluctuations shown in Figure 3. The large pressure decrease associated with the storm lasted for a day or so, and as a result the water level in the well showed a steady and uninterrupted rise during this period.

Earthquakes

Some of the most interesting water-level fluctuations observed in artesian wells are those caused by earthquakes occurring hundreds to thousands of miles from the wells. The distant earthquakes go unnoticed in the state because the shock waves that affect the water in the ground are not perceptible to human beings, and there are no visible effects, such as movement of the ground and shaking of buildings. Figure 7 shows the simple but striking pattern produced in an artesian well in Dougherty County, Georgia, by an earthquake which occurred in Mexico. Because of the condensed time scale used on such a gage (which was not designed for earthquake work) the disturbance was recorded as a vertical line above and below the water-level trend showing the rise and fall of the water level when the shock waves arrived at the well. The aftershocks which followed the main waves are shown by the solid lines immediately to the right of the vertical line. After the waves passed the well the normal fluctuations of the water level continued uninterrupted, and except for the shock record produced it would never have been known that the water within the earth was so rudely disturbed for a short period of time. Such fluctuations, although not rare, are uncommon when the total number of artesian wells in Georgia or the entire country is considered.

Moon and Sun

Strange as it may seem the moon and sun have a pronounced effect on the ground water within the earth's crust, both inland and near the seacoast. The heavenly bodies affect water levels in two different ways — through pressure effects of ocean tides and through pressure effects on confining beds by earth tides. Along the coastal areas of Georgia ocean tides influence the water levels in wells drilled in an artesian aquifer which extends beneath the Atlantic Ocean, and several hundred miles inland in north Georgia, far removed from the influence of ocean tides, earth tides affect the water levels in deep wells drilled in crystalline rocks such as gneiss, granite, schist, and quartzite.

Earth Tides

Figure 8 shows the effects of earth tides on the water level in a 400-foot well in crystalline rocks in north Georgia. This well is about 240 miles west of the Atlantic Ocean and 300 miles north of the Gulf of Mexico, and is too far inland for the water in the well to be affected by ocean tides. We refer to the fluctuations as being caused by earth tides as distinguished from ocean tides because both types of fluctuations are caused by the attractive force of the moon and to a lesser extent of the sun. Because the moon rises 50 minutes later each night the daily high and low water levels in the well also occur 50 minutes later each day. The magnitude of the water-level fluctuations in the well varies with change in phase of the moon. The largest fluctuations occur during periods of new and full moon when the moon, earth, and sun are in a line with each other and the tide-producing forces are greatest, and the smallest fluctuations occur during the first and third quarters when the three heavenly bodies are out of phase with each other and the tide-producing forces are smallest. This figure illustrates a cyclic graph which repeats itself about every 28 days when the moon completes one revolution around the earth.

Ocean Tides

Figure 9 is a cyclic graph showing water-level fluctuations caused by ocean tides in an artesian well near Savannah, Georgia. Simply stated, the water level in the well responds to the daily ocean tides because the changing tidal load placed on the artesian aquifer causes the pressure to alternately increase and decrease in the aquifer. That is, when the tide moves inland the added weight of water compresses the aquifer and the water pressure increases and forces water into the

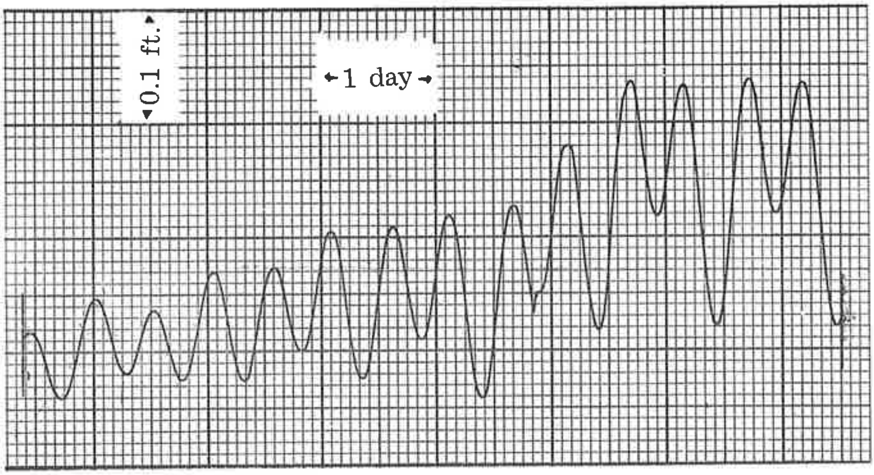


Figure 8. Water-level fluctuations caused by earth tides.

well and the water level rises. Conversely, when the tide recedes the added weight on the aquifer is removed, the pressure decreases and water levels in this type of tide.

The graph illustrates fluctuations repeated at regular intervals and the pattern shows a rise and fall of the water table in response to the daily high and low tides. As noted on the figure there are two high and two low water levels each day, corresponding to the daily occurrences of the ocean tides. We refer to the tides as diurnal because the full tidal cycle of high and low water is completed in half a day; in other words, in a day there are two high and two low waters in this type of tide.

FLUCTUATIONS CAUSED BY PUMPING

The pumping of an artesian well may have a very pronounced effect on the water levels in nearby wells, and in many cases periods of continuous and intermittent pumping, especially the latter, may mask completely the normal ground-water pattern in an area. When the water level in a well is affected by pumpage from another well hydrologists commonly refer to this as interference between wells. The greatest number and range of fluctuations occur during cyclic pumping because the water table does not have time to stabilize, and it is continually changing during these periods — declining when the pump cuts on and rising when the pump cuts off.

Figure 10 shows the water-level fluctuations in an artesian well in Chatham County, Georgia, caused by ocean tides and upon which are superimposed the effects of nearby pumping wells. The graph is

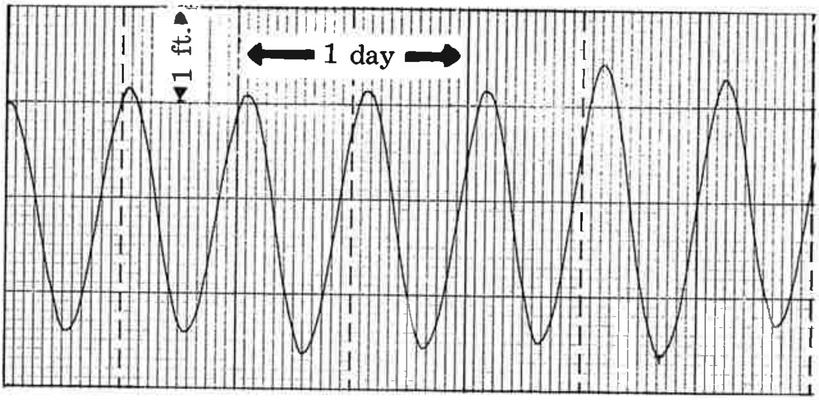


Figure 9. Water-level fluctuations caused by ocean tides

more striking than the one shown in Figure 9 because an additional repetitive pattern has been added to the cyclic pattern produced by ocean tides, and a simple graph now becomes complex.

Figure 11 shows typical water-level fluctuations in 4 artesian wells in south Georgia during periods when a nearby well was being pumped. The cyclic patterns of the graphs were due to periods of intermittent and continuous pumping of nearby artesian wells which caused the water table to oscillate rapidly. The solid segments on the graphs were caused by rapid fluctuations of the water table during repeated starting and stopping of the pumps, and the blank or non-recorded portions on the graphs represent nonpumping periods during recovery of the water table.

Figures 11A and 11C show the effects of cyclic pumping during periods when the water table in the areas was steadily rising, and Figures 11B and 11D show the water levels during periods when the water table was declining. The large changes in water levels shown in Figures 11A, 11B, and 11D caused the chart drums on the instruments to turn one or more revolutions and as a result the records were traced around the charts as the drums revolved. The periods of more or less continuous pumping resulted in a mass of solid segments on the graphs of Figures 11A and 11D, whereas the pumping periods were less frequent and the pattern of the graphs were more open in Figures 11B and 11C.

Some of the most interesting and unusual ground-water patterns, and certainly the most distinctive observed by the author, are shown in Figure 12 for 4 artesian wells in Tennessee. The records of the wells were made available by the District Geologist, Ground Water Branch, Memphis, Tenn.

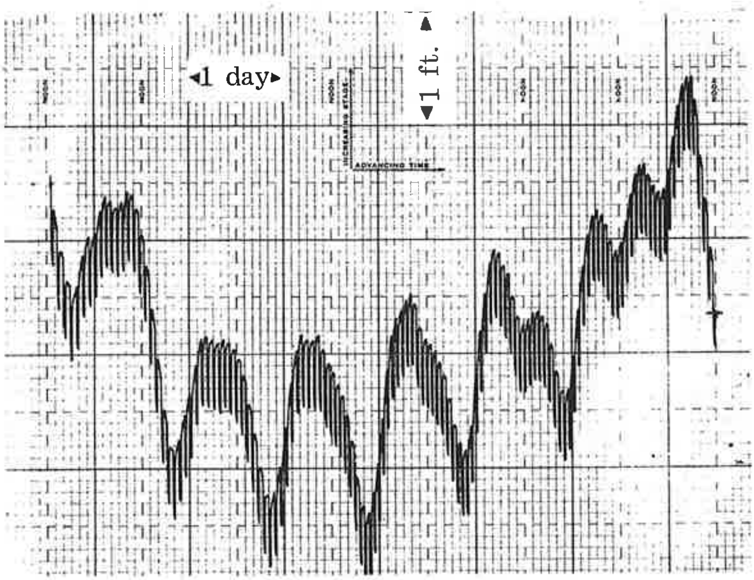


Figure 10. Water-level fluctuations caused by ocean tides and nearby pumping wells.

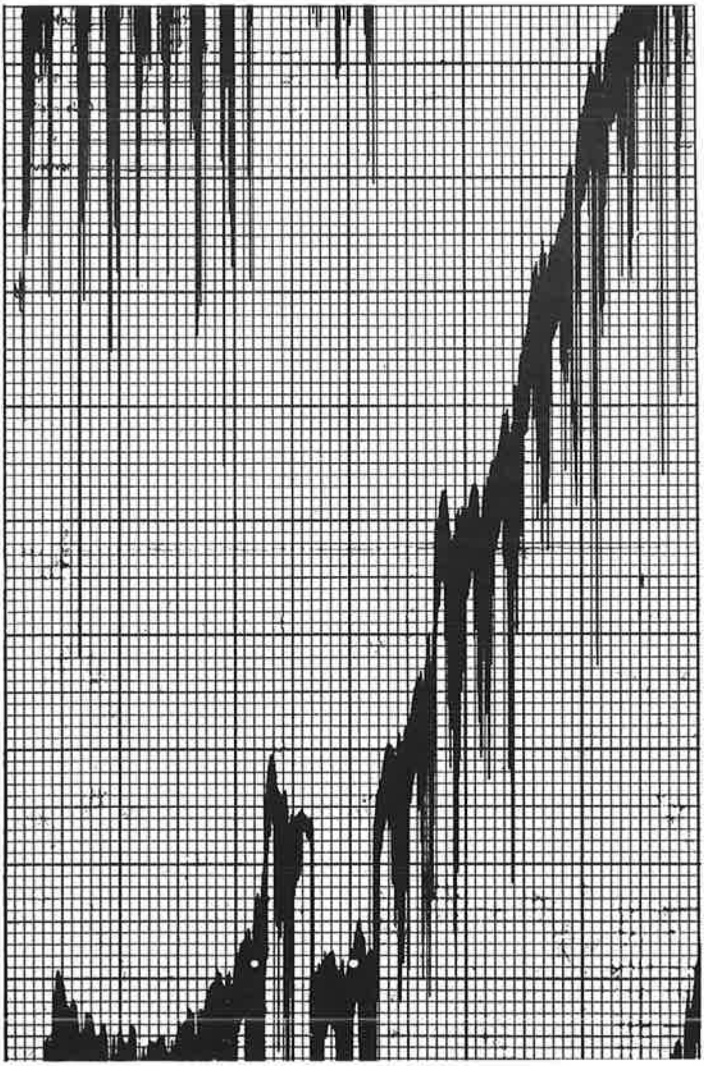
These graphs, in addition to those shown in Figure 11, illustrate the complex ground-water patterns produced when the normal water table is disturbed by the effects of pumping. The added fluctuations superimposed on the graphs completely obscure the natural fluctuations of the water table, and it is difficult to determine the true ground-water levels in the wells. Moreover, the nonpumping periods were too short to allow complete recovery of the water levels in the wells before the beginning of a new pumping cycle. As a result, such graphs, although quite spectacular, are often difficult to analyze and generally require more time to plot than the simple graphs shown in Figure 1.

SUMMARY

The ground water in the earth's crust is in a continuous state of motion — at times moving ever so slowly and at other times fluctuating rapidly over a wide range. These disturbances of the ground water are due largely to a variety of natural causes, but man may impose additional effects on the system (for example, pumping of wells) and thereby complicate the natural ground-water pattern in an area. The patterns and designs produced by the changing water table may range from a simple graph showing very little fluctuation to a complicated graph showing a wide range and variety of fluctuations. Thus, the water level in one well may not respond to any outside influences other than rainfall or the lack of it, whereas another well may respond simultaneously to several natural causes such as atmospheric pressure changes, ocean tides, and wind.

Most of the major natural causes of water-level fluctuation are cyclic and for this reason we can expect them to show up year after year. Thus we can expect the ground water to be recharged annually by rainfall, the atmospheric pressure to continue to act on the entire aquifer system, the moon to cause the water level to change because of the resulting effects of ocean tides and earth tides, and so forth. On the other hand, some natural causes which affect the water table are not predictable, as for example fluctuations caused by earthquakes. Man-made patterns produced by continuous and intermittent pumping of wells will change with the season, but generally the fluctuations of the water table are about the same year after year.

Water-level fluctuations produced by natural and man-made causes produce characteristic patterns which generally are easily identified unless masked completely by other effects. Thus, earthquake patterns differ from the patterns caused by ships, atmospheric-pressure change patterns differ from those caused by ocean tides, and patterns produced by pumping of wells differ from those due to recharge of the aquifer from rainfall.



A

Figure 11. Water-level fluctuations in artesian wells in Georgia caused by pumping of nearby wells.

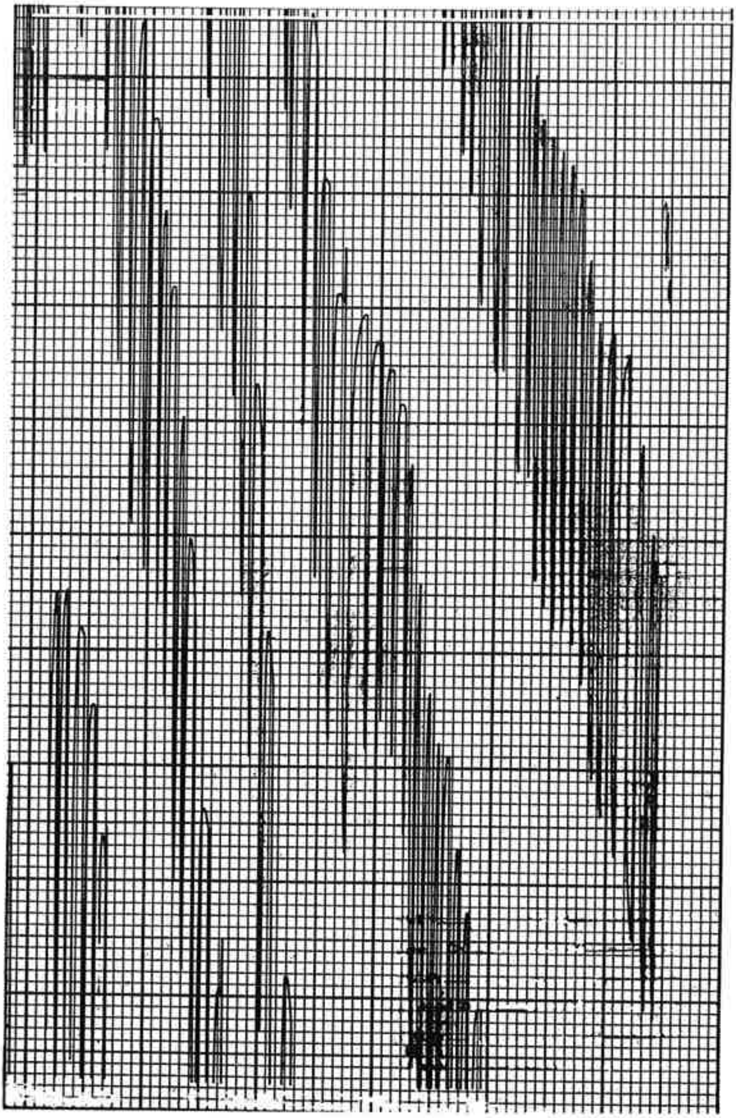


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Figure 11. Water-level fluctuations in artesian wells in Georgia caused by pumping of nearby wells.

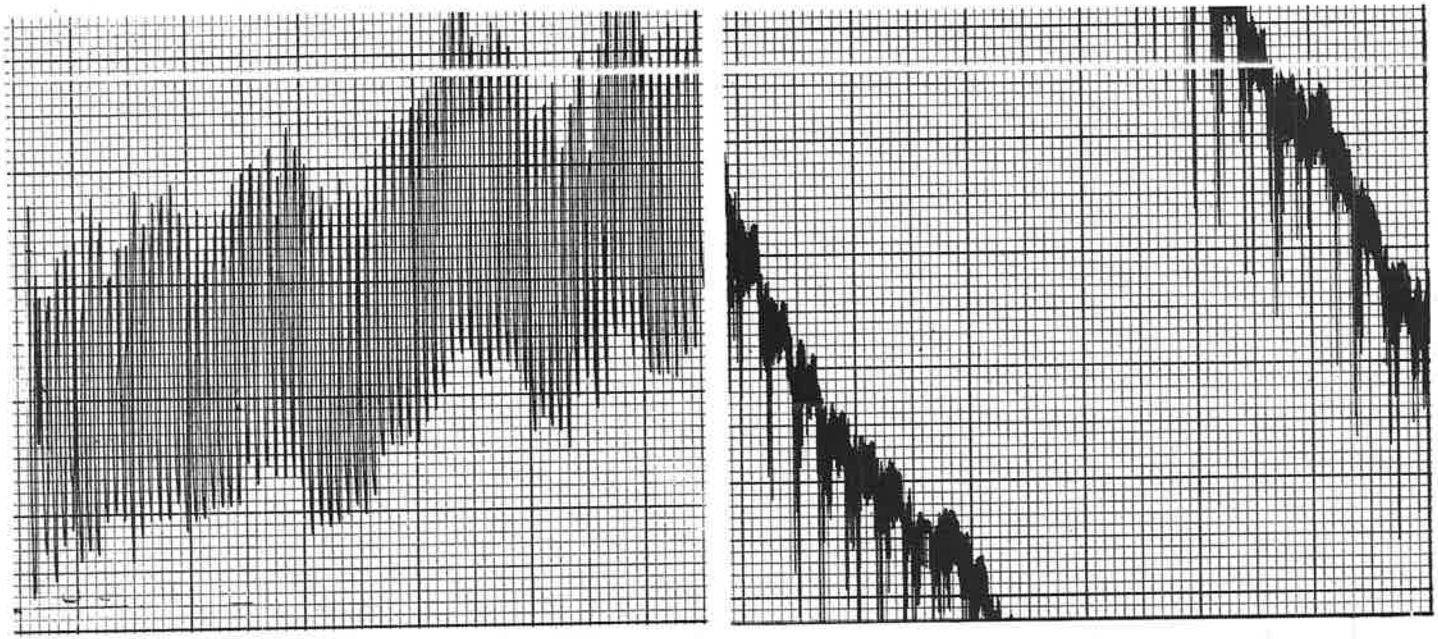

Figure 11. Water-level fluctuations in artesian wells in Georgia caused by pumping of nearby wells.

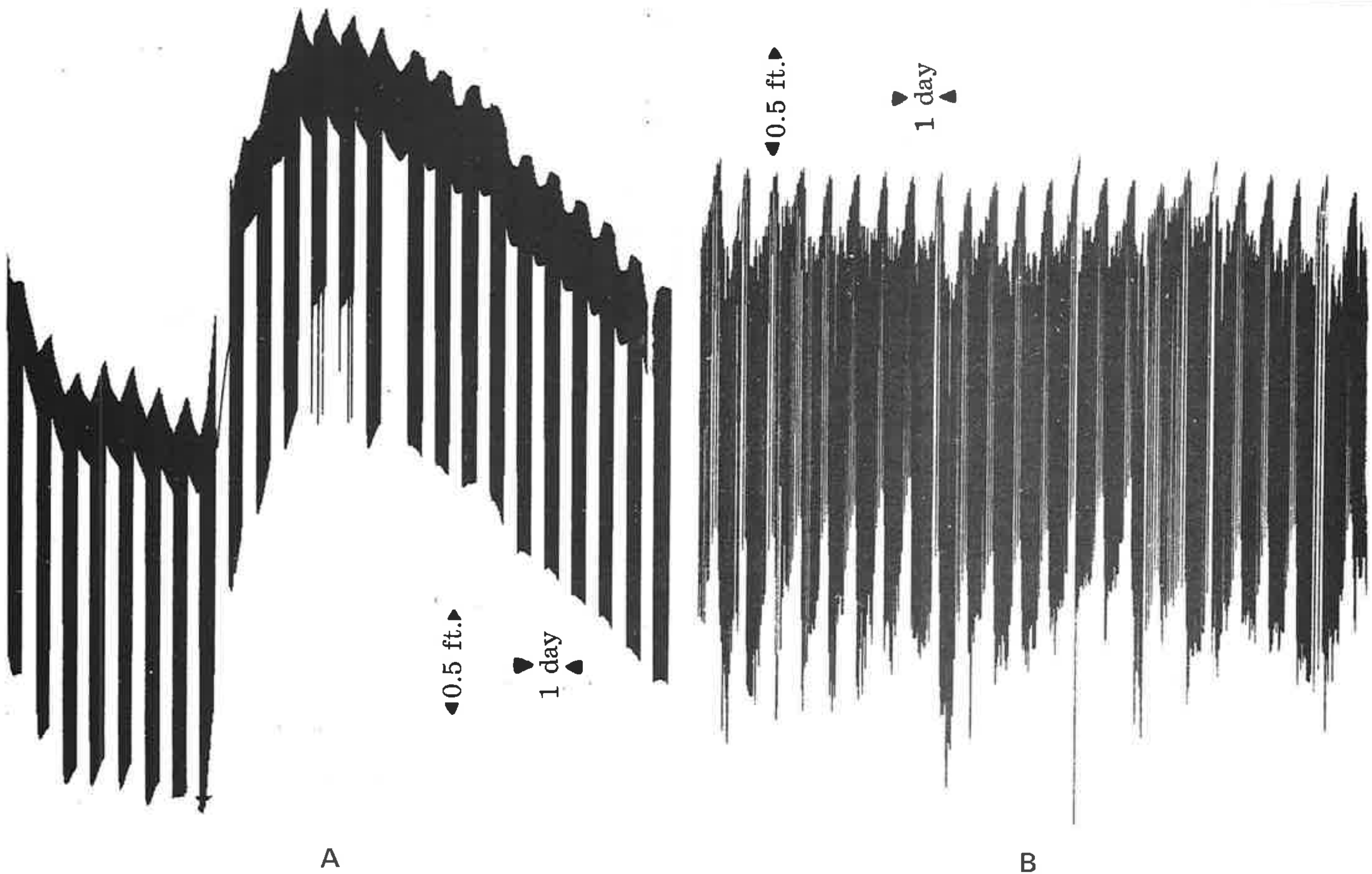

Figure 12. Water-level fluctuations in artesian wells in Tennessee caused by pumping of nearby wells.

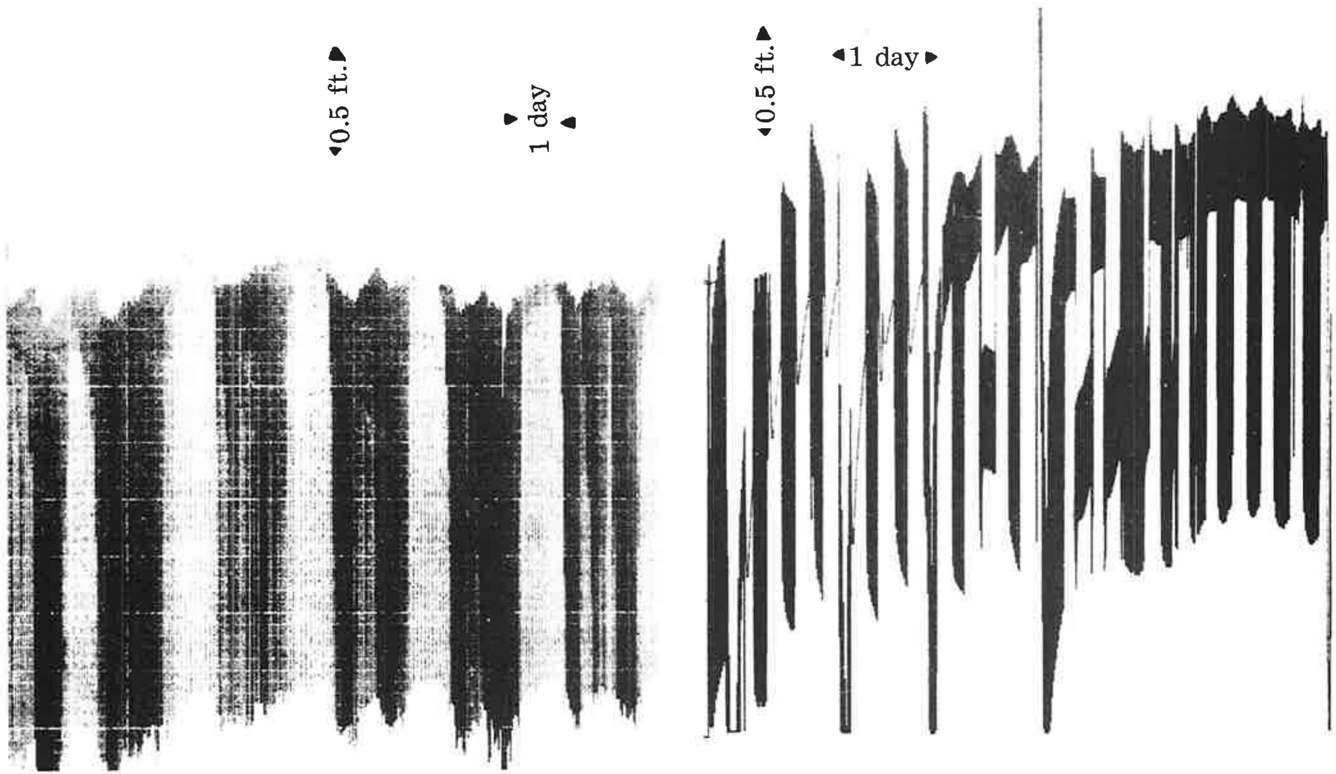

Figure 12. Water-level fluctuations in artesian wells in Tennessee caused by pumping of nearby wells.

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