

Geology. — *The origin of artesian pressure.* By J. VERSLUYS.

(Communicated at the meeting of March 29, 1930.)

Underground water is called artesian water, and it is said to have artesian pressure if its pressure head is sufficient to lift it to a level higher than the surface of the ground (24). This conception prevailed in the beginning of the nineteenth century in France where many artesian wells were drilled at that time (1, 2, 3). From a theoretic standpoint the meaning of the term artesian is not very essential. Suppose the pressure head of a certain layer varies little or not over a great area. Then, if the surface of the earth is rolling at certain places the pressure head may, but at other places may not be able to make the water rise higher than the surface. In low places there may be artesian water in relatively shallow sands, while at adjacent spots where the surface of the ground is higher, artesian water only occurs in deeper sands or does not exist at all. Consequently the water of a layer may be artesian at one place and may not be so at some distance.

A question of preponderant importance from a theoretic point of view is, whether or not the pressure head of the water increases with depth. That means, whether the water of deeper strata will rise higher than shallow water. In digging a well at a depth which as a rule is not very great, water will be encountered which fills the well to a certain level. At this level the phreatic surface has been reached and the water flowing into the well is phreatic water. This water occurs as well in sandy as in clayish formations, the difference being only that the coarser the texture of the ground the faster water will flow into the well. In real sands a well may be drilled deeper without showing any variation of pressure head. As soon as a less permeable layer has been passed however, the water of deeper sands may have a different pressure head. The pressure head of such water may be either greater or smaller than for the phreatic water. In valleys as a rule the pressure head increases at every less permeable layer which is passed and this may also be the case in plains or low-lying tracts, offset by hills or mountains. This phenomenon also often occurs in coastal plains gradually rising to inland hills or mountains.

In case there are only strata of a finer texture, we may meet this increase of pressure head with depth also in valleys and plains, without any real change of texture with depth, but generally such is not observed. Water will fill wells, drilled into a clay or a loam, so slowly, that one can hardly get any water from it and measurements are seldom done. In case however two sands with different pressure heads are separated from each

other by a clayish, so called impervious layer, then the pressure head in the clay will gradually change with depth in the clay.

As it has been stated before, in very pervious strata difference of pressure head with depth will be negligible. As soon as there are less pervious strata or an alternation of more and less pervious strata, the variations of pressure head with depth may be considerable and the occurrence of artesian pressure will often be the result.

The occurrence of artesian water and more generally the increase of pressure head with depth, means an upward motion of water. Generally speaking, the lateral motion in the more pervious strata will be many times faster than the upward motion, while in the less pervious strata, if they are intercalated with more pervious layers, the lateral motion will be very slow, even negligible compared to the vertical motion. So artesian regions are districts where ground water from depth rises and tends to join the phreatic water, which is either drained solely by rivers, canals, lakes or by the ocean, or also partly and exceptionally entirely by capillarity and vegetation which ultimately means evaporation.

In the same way, regions where the reverse occurs, when pressure head in deeper strata is smaller than in shallow layers and where in any point at depth of a vertical pressure head is too small to enable the water to rise to the point of intersection of the vertical with the phreatic surface, all groundwater has a downward motion.

According to these principles, the author's conception of underground water conditions, as they were developed in 1914 (7) is a dynamic one, and it would not preclude the occurrence of artesian water, even in formations which consist of so called impervious strata. An increase of pressure head with depth is, as it will be explained hereafter, promoted by the presence of lenses of more pervious material and still more by persistent pervious strata, f.i. sheet sands.

The origin of artesian pressure was in 1691 explained by BERNARDINI RAMAZZINI (*De fontium mutinensium admiranda scaturigine physico-hydrostaticus*, Modena, 1691). DAUBRÉE (6, p. 153) gave an illustration of the phenomenon according to RAMAZZINI's explanation like figure 2.

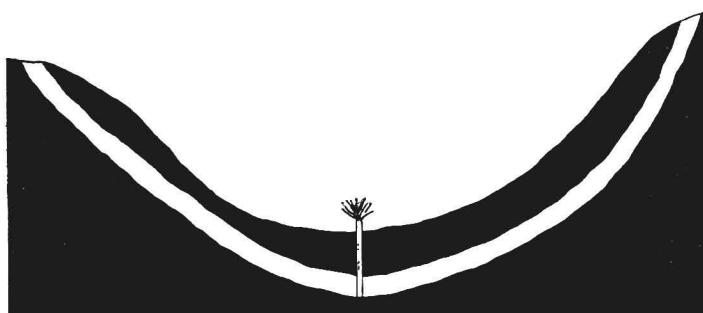


Fig. 1.

In the beginning of the nineteenth century a great number of artesian wells had been drilled in France and in England and knowledge of artesian water had increased. In 1822 (1) F. GARNIER gave an illustration of a persistent pervious layer interstratified between impervious layers outcropping in a high-lying tract and extending under a plain. (Fig. 3.) The

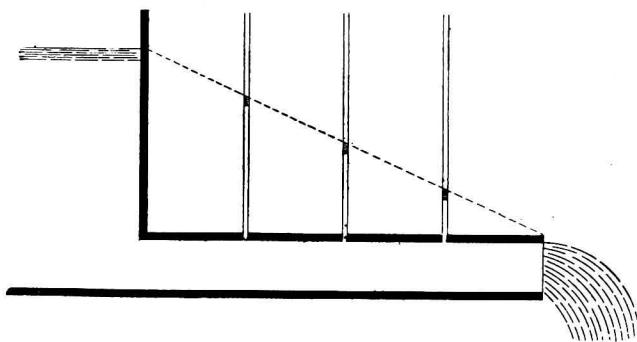


Fig. 2.

intake area which would feed the artesian water by percolation of atmospheric water, would only be the narrow zone of the outcrop of the artesian aquifer.

The explanation of GARNIER and RAMAZZINI implied a dynamic condition. In 1834 ARAGO (3) compared the artesian water with water in a *U*-tube. ARAGO did not add any illustration to his description, but his idea was the origin of figure (1) which is very popular. This conception which was inspired by the artesian basin of Paris, is less general than the

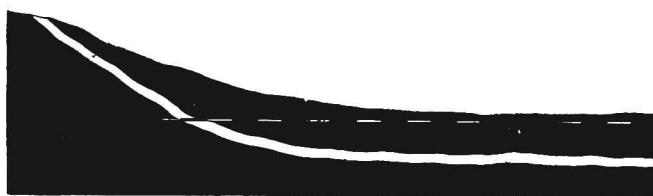


Fig. 3.

theory of RAMAZZINI and GARNIER and it does not so well elucidate the dynamic condition of artesian water.

In 1893 some doubt arose about the theory of RAMAZZINI and GARNIER regarding the conditions of artesian water in Queensland and New South Wales (23, pp. 412 and 413). All the artesian wells in these countries derive their supplies of water from sands and fine gravels of the lower cretaceous formation. In Queensland the total outflow of all the wells was estimated to be greater than the volume of water which could be replenished by atmospheric water percolating in the area of the outcrop

The artesian water of Batavia (D. E. I) was till 1911 supposed to be supplied by three sheetsands, and according to the general dip of the strata, the outcrops of these sands were supposed to be approximately known. The conception perfectly accorded with GARNIER's idea (Fig. 3). In 1911 however as cross sections were drawn through the numerous artesian wells, it appeared that there were no persistent sands at all. The sands were lenticular and the various lenses were not very extensive. In 1914 the writer (7) developed his principles concerning the motion of underground water, in which pressure-differentials were explained. It appeared that alternation of strata of different permeability is not necessary for giving rise to an increase of pressure head with depth and to artesian pressure. Only, as has previously been mentioned, alternation of more and less permeable strata yields favorable conditions, not only for the detection, but also for the rate of increase of pressure with depth. The author's conception, in case there are real persistent sheet sands, does not limit the area which recharges the so called "aquifer" to its outcrop. The word "aquifer" and synonymous expressions are generally applied to the more pervious layers, as such layers are the main bearers of horizontal movement of water. They are the only layers really giving evidence of pressure differences and yielding water in an appreciable quantity to a well. We must however not lose sight of the fact, that less permeable, so called impermeable strata, contain water as well as the "aquifers" and under a similar pressure head.

Movement of underground water is controlled by the same fundamental law as the conductivity of electricity and provided the boundary conditions are steady, also as the conduction of heat. In comparing flow of underground water to conduction of heat, temperature must be taken for pressure head. Lines of equal temperature coincide with lines of equal pressure head, and lines of flow are the same for groundwater and heat.

Suppose a sheet of a conductive material, with two plane faces, lies horizontally on a non-conductive material (see Fig. 4). In the upper face

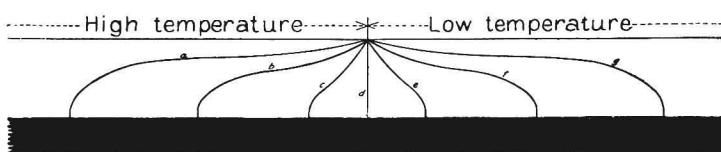


Fig. 4.

the temperature is constantly kept at a high temperature on one side of a certain straight line, and at a low temperature on the other side of the line. Heat will flow through the conductive sheet from the portion where temperature is high at the surface to the other, and lines of equal temperatures will be somewhat like the curves in Fig. 4. These curves show different temperatures, highest in *a*, lowest in *g*. So here we see in

the portion of the sheet where temperature at the upper face is low, an increase of temperature with depth, in the portion of high temperature at the face on the contrary temperature decreases with depth.

Such conditions f.i. are prevalent in Holland where deeper polders are in contact with polders of smaller depth, or with canals and lakes. But as a rule with underground water, conditions are somewhat different. Assume the non-conductive solid, which is the base of the conductive sheet, has a protuberance as shows Fig. 5, and the conductive sheet again makes contact with the face of the basal solid. The upper face of the conductive

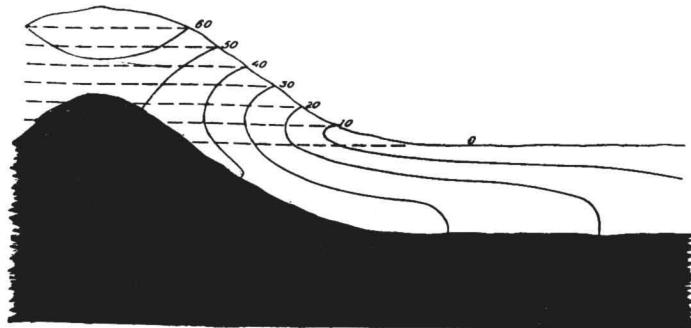


Fig. 5.

sheet has a bump over the protuberance of the non-conductive solid. The low-lying horizontal portion of the face is constantly kept at a temperature zero, while in the protuberance temperature at the face increases directly as the elevation. The intersection of the lines of equal temperature with the plane of cross section (Fig. 5) will be formed like the curves in the diagram and the figures at each curve indicate the respective temperatures. On the right side of the protuberance temperature increase with depth. Suppose, instead of the conductive material there is a sheet of loam or clay, which is exposed to the atmosphere and its precipitation. In the protuberance, water from rain, snow and mist partly percolates. Due to the resistance, the clay exerts on the water as it flows, the clay will be saturated with water to a level which generally is not much below the surface at any point. So the phreatic surface will have a shape not much deviating from the surface of the ground. The flat part of the surface in Fig. 5 corresponds to the low-lying tracts. In such tracts there are as a rule riverbeds, which drain the ground to a certain level, which varies with the seasons. In plains outside riverbeds, as a rule water also will percolate, till it reaches the phreatic surface which has a slope towards the riverbeds. In this part of the territory however at depth groundwater will rise and also be drained by the riverbeds. In plains the shape of the phreatic surface is largely controlled by riverbeds. The surface of equal pressure head are shaped like the curves which as long as we were dealing with heat, were the lines of equal temperature in Fig. 5.

It is not necessary to adapt the examples still more to what takes place in nature. The possibility of an increase of pressure head with depth being arising in a homogeneous formation has been elucidated. In case the homogeneous formation is very permeable like sand, in the protuberance or the hill, water would sink so easily that the phreatic surface would not be much higher than in the plain. Hence very permeable formations are unfavorable for the occurrence of pressure head with depth.

Theoretically, increase of pressure head with depth may occur in homogenous formations, which are not very permeable, provided the surface of the earth is rolling or inclined, and the formation is not very pervious. Further such increase of pressure head is promoted by lenses and still more by persistent layers of more permeable sediments. If such lenses or layers fail, generally little attention is devoted to the pressure of ground-water and it will not at an appreciable rate flow out of wells. As it has previously been explained, artesian pressure is merely a not infrequent excess of the described phenomenon.

Adopting "rockpressure" to explain artesian pressure, as it was done by R. HAY (19) in 1890, later on by J. W. GREGORY (20), is not at all necessary, not even if the bearer of artesian water does not outcrop or if the artesian water occurs in lenses. If artesian pressure were caused by rockpressure, taking water from artesian wells would imply a subsidence of the surface, as it has been recognized by several authors, although subsidence caused by artesian wells has not been proven (11 and 12).

Such subsidence is possible, due to the fact that clay strata can be compressed as long as a film of absorbed water separates the solid particles (25). This has actually taken place in the Goose Creek Oil field near Houston (Texas), according to the conception of W. E. PRATT and D. W. JOHNSON (16, see also 17 and 18) which is very plausible. In deep seated oil strata however after a long period of exploitation, pressure decreases several hundred pounds, while in artesian layers, pressure seldom decrease more than 10 or 20 pounds on account of the withdrawal of water. This small decrease of pressure due to artesian wells cannot warrant a considerable compaction of strata, able to counterbalance the huge volumes of water withdrawn from depth by means of artesian wells.

Moreover one must not forget that in many cases pressure has been relieved by erosion. So further compaction of sandstones by variation of pressure which are not enormous would be negligible. Clays may expand again when pressure is relieved, but an appreciable compression can only be caused by a considerable variation of pressure, which generally is not caused by artesian wells, but may be caused by exploitation of oil fields.

Artesian "aquifers" will not easily be exhausted. The area which feeds such by percolation of atmospheric water, is much larger than the outcrop zone. As soon as water is withdrawn from the artesian "aquifer" the recharging zone will extend. From a larger area water will flow through other strata to the "aquifer", due to the decrease of pressure. Furthermore

less water will rise from the artesian aquifer to overlying strata, even the flow may be reversed. So by withdrawing water from an "aquifer" direction and speed of flow not only in the "aquifer" itself, but also in other strata will be modified. As it has been stated, more water from underlying strata will flow into the "aquifer", due to the decrease of pressure. This means that water from an area which formerly did not reach the aquifer, now will do so, and it could be said that the recharging area has extended. Water from the artesian "aquifer" partly will escape into the overlying strata. This loss will become smaller, and may even be converted to a gain on account of the decrease of pressure caused by artesian wells.

Flow of underground water mainly takes place in the more pervious layers. Hence in pervious layers connate water will sooner be washed out by water which has percolated from the area which feeds the "aquifer". In 1915 the author recognized this phenomenon in the coastal regions of Holland¹⁾ (29 and 30). Where fresh water from the coastal dunes is penetrating, sandy strata may contain fresh water, while the clays generally still contain the water from the ocean which had saturated them during a former period. So we must be prudent in basing our conclusions on the chemical analysis of underground water. Evidence of salt water being replaced by fresh water, is presented by the occurrence of so called "alkaline waters" (28)¹⁾.

Changes of height of water in the ocean, due to tides, and in rivers and lakes, interfere with pressure of groundwater. Such variations are often observed with artesian waters (7, 21, 22, 31, 32). This phenomenon can easily be explained. The solid material of the strata is practically incompressible

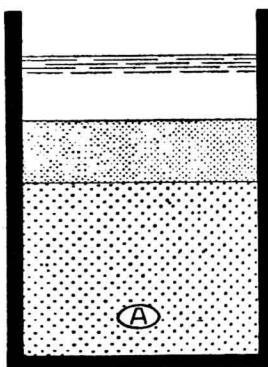


Fig. 6.

within the range in which pressure varies, and the same is true for the water in the pores. Say we fill a reservoir partly with sand, cover this sand with clay, both saturated with water (Fig. 6). The pressure head of the water in the sand at a point A will coincide with the surface of the water in the reservoir. If water is added, the pressure head at A will increase as much as the surface of the water is raised. There is a direct communication and the pressure increases without any displacement of the solid or the liquid. Nevertheless, by some authors the interference of tides with artesian pressure is explained as a consequence of

the greater load on the strata, through compression. Generally the variations of artesian head are smaller than the variations of height of water which causes them. This circumstance has also been adopted as a proof of the theory that tides interfere with artesian pressure by changing

¹⁾ A new article on this subject will soon appear in Economic Geology.

the load and compressing the strata. Figure 7 however, shows that such can be explained also without any compression.

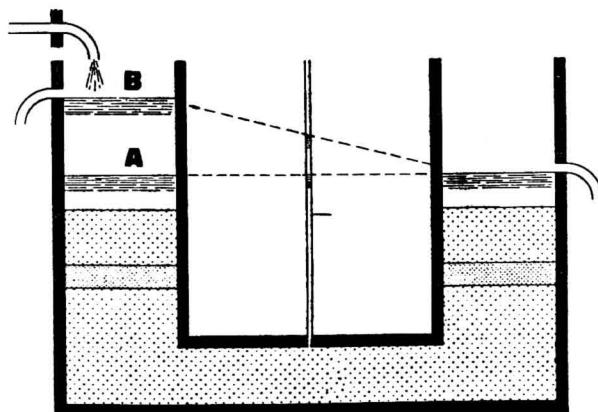


Fig. 7.

LITERATURE.

1. F. GARNIER: "De l'art du fontenier sondeur et des puits artésiens", 1822 and "Traité sur les puits artésiens", Paris, 1826.
2. HÉRICART DE THURY: "Considérations géologiques et physiques sur la cause du jaillissement des eaux des puits forés ou fontaines artificielles, etc.", Paris 1829.
3. ARAGO: "Sur les puits forés, connus sous le nom de puits artésiens, de fontaines artésiennes, ou de fontaines jaillissantes". Annuaire pour l'an 1835 présenté au Roi par le bureau des longitudes", pp. 181—258.
4. DÉGOUSÉE et CH. LAURENT: "Guide du sondeur ou traité théorique et pratique des sondages". Vol. I. 2nd Edition, Paris 1861.
5. H. DARCY: "Les fontaines publiques de la ville de Dijon". Paris 1856.
6. A. DAUBRÉE: "Les eaux souterraines à l'époque actuelle", Vol. I, Paris 1887.
7. J. VERSLUYS: "Contribution à la théorie de l'écoulement de l'eau souterraine". Amsterdam 1914.
8. J. H. GARDNER: "The Mid-Continent Oil Fields". Bulletin Geol. Soc. Am. 28, p. 702, 1906.
9. J. VERSLUYS: "Hydrologisch inzicht". Water en Gas, 1925, pp. 141—143.
10. _____: "De theorie van het artesische water van GARNIER. Water en Gas", 1926, pp. 235 and 237.
11. W. L. RUSSELL: "The origin of artesian pressure". Economic Geology 23, pp. 132—157, 1928.
12. O. E. MEINZER: "Compressibility and elasticity of artesian aquifers". Economic Geology 23, pp. 263—291, 1928.
13. A. M. PIPER: "The origin of artesian pressure". Economic Geology 23, pp. 683—696, 1928.
14. S. TABER: "Effect of earthquakes on artesian waters". Economic Geology 23, pp. 696—697, 1928.
15. CH. TERZAGHI: "The origin of artesian pressure", Economic Geology 24, pp. 94—100, 1929.
16. W. E. PRATT and D. W. JOHNSON: "Local subsidence of the Goose Creek Oil field", Journal of Geology, 34, N°. 7, Part 1, pp. 577—590, 1926.

17. L. C. SNIDER: "A suggested explanation for the surface subsidence in the Goose Creek oil and gas field". Bull. Am. As. Petr. Geol. **11**, pp. 729—745, 1927.
 18. W. E. PRATT: "Some questions on the cause of the subsidence of the surface in the Goose Creek Field, Texas". Bull. Am. As. Petr. Geol. **11**, pp. 887—889, 1927.
 19. R. HAY: „Artesian wells in Kansas and causes of their flow”. Amer. Geologist, **5**, pp. 296—301, 1890.
 20. J. W. GREGORY: "The dead heart of Australia". JOHN MURRAY, London 1906, pp. 288—289.
 21. J. W. VEATCH: "Fluctuations of waterlevel in wells, with special reference to Long Island, N.Y." U.S. Geol. Survey Water supply paper **155**, pp. 62, 63, 65—69, 74, 75, 1906.
 22. M. L. FULLER: "Summary of the controlling factors of artesian flows". U.S. Geol. Survey. Bull. **319**, p. 33, 1908.
 23. T. W. E. DAVID: "Notes on artesian water in New South Wales and Queensland", Journal of the Royal Society of New South Wales, **27**, p. 408—431, 1893.
 24. J. VERSLUYS: "Wat zijn artesische putten"? De Ingenieur, 1926, pp. 805—806.
 25. _____: An hypothesis explaining some characteristics of clay", Proceedings Royal Academy of Sciences in Amsterdam, Vol. **30**, pp. 104—112, 1927.
 26. _____: "The compacting pressure of sediments". Proceedings Royal Academy of Sciences in Amsterdam, Vol. **30**, pp. 1004—1009, 1927.
 27. _____: "Synclinal oil and unsaturated strata". Proceedings Royal Academy of Sciences in Amsterdam, Vol. **31**, pp. 1086—1090, 1928.
 28. _____: "Chemical actions in the subsoil of the dunes". Proceedings Royal Academy of Sciences in Amsterdam, Vol. **18**, pp. 1619—1624, 1916.
 29. _____: "Hydrologie van het Nederlandsche Kustgebied", Water, Vol. **1**, 1917—1918.
 30. _____: "Over het duinwater", Trans. Geol. Section Geol. Mijnb. Gen. for Netherland and its Colonies, Vol. **2**, pp. 24—30, 1915.
 31. _____: "Rapport omtrent het geo-hydrologische onderzoek, verricht in verband met het opmaken van plannen voor een centrale drinkwatervoorziening in de provinciën Zuid-Holland, Noord-Holland en Utrecht", the Hague, 1919.
 32. J. H. STEGGEWENTZ: "Bijdrage tot de kennis van den invloed van de getijbeweging op de stijghoogte van het grondwater". Mededeeling N°. 9 van het R. V. D. the Hague, 1929.
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