Applying this also to the ordinary non-gravity flow-formulas, the correct values for the flux are obtained, as verified empirically.

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Gulf Research and Development Corporation,
Pittsburgh, Pennsylvania

## HISTORICAL DEVELOPMENT OF IDEAS REGARDING THE ORIGIN OF SPRINGS AND GROUND-WATER

M. N. Baker and R. E. Horton

The origin of water has been the subject of speculation ever since the formulation of tradition and myths regarding the creation of the world. But at the very beginning of Greek philosophy speculation turned from water, as one of the four elements, to the origin of springs.

Priests, poets, philosophers, naturalists, and engineers took up the subject in somewhat the order named. Then came the specialized scientists--astronomers, geographers, meteorologists, and hydrological engineers. From time to time the encyclopedists include springs in their grand summaries of all knowledge. The gross result has been an enormous mass of writing on the origin of springs. The net result has been a small body of well-considered theory, supplemented now and then with data and deductions. Of the 50 to 100 men who have written at some length on the subject, the utterances of a large percentage of the more significant or entertaining have been gathered and examined by one or other author of these notes, going back to original sources where libraries and time made that possible--translations in the case of classics and some other authors. Of the 60,000 words of source-material thus far amassed, only a small portion, and that chiefly by summary, can be given within the limits of this paper. Later it is hoped that much, if not all, the source-material, with critical comment, can somewhere be published.

By way of preliminary summary it may be stated that beside the now well-known and almost universally accepted pluvial origin of springs--the evaporation-condensation-precipitation-percolation cycle--there persisted from the earliest times until well into the nineteenth century, the ocean-fed theory. The latter was upheld by two schools: One, and the more general, believed that water passed from the ocean through subterranean channels and up to the surface of the Earth. The other believed that, instead of flowing through a few large channels, it percolated through an infinitude of small ones between layers of sand or other permeable material. In either case the water rose to the tops of hills and mountains. Many and various were the attempts to explain what lifted the water to such great heights and what became of its saltness. As to the motive power, some thought the water was vaporized and lifted by the internal heat of the Earth; others held that it went up by capillary action; still others that water circulated like sap in a tree or blood in man; others said that the motive force was the stars or the tides. As to what became of the salt, the first school held that it was deposited in the caverns and the second in the interstices of the Earth, both schools alike not troubling to tell why these did not fill up, or else offering fanciful explanations.

Broadly, the theories of the origin of springs followed one or another cosmogany, either the Hebrew creation by fiat or some one of the rational doctrines of the Greek philosophers who consider water as one of the four elements and go back of that to the "seeds" of "first beginnings" or atoms.

The seventeenth and eighteenth centuries were prolific with theories of the origin of springs. A large percentage of these were presented in sermons, essays, and books written to show the goodness of God and to uphold Creation by Design. Some of these combined the Hebrew and Greek cosmologies so far as to identify the Tartarus of Homer and Plato with the Great Abyss of Moses.

Abstract conceptions rather than observed facts were the basis of most of the theories for more than 1500 years. Some of these were illuminated by the lights of both reason and nature. Where natural phenomena were observed, they were limited and local. When of broader geographical range, vague reports were accepted and wrongly interpreted. This was truer in the earlier than the later centuries, but dogma often blinded reason even into the nineteenth century.

Although the pluvial origin of rivers was announced by Aristotle and accepted by many from that time on, yet more than a millenium passed before rainfall- and runoff-data to support this theory were accumulated and published or even such simple field-observations were made and recorded as tracing streams to their minute and multifarious sources in springs and mere oozes of moisture. A glimmering of the importance of elevated, exposed, pervious, water-receiving strata and accompanying impervious strata was seen and noted by the architect-engineer Vitruvius just before the birth of Christ. Its significance was almost or quite ignored until comparatively recent times. It was not until near the close of the eighteenth century that what became known as the Strattonian theory of stratification was announced. This pointed the way to an understanding of the origin not only of springs but of all underground waters.

Before taking up specifically some of the theories of the origin of springs a few words may be said about comprehensive reviews of the subject that have been written in the past. The first of these was by Seneca, at the close of the classical period (about 60 A.D.). In the eighteenth, nineteenth, and twentieth centuries, four pluvialists and one believer in the ocean-fed theory reviewed the subject. Of the pluvialists, all were engineers--three French and one a German. These men and the dates of their publications were: Perrault, 1674; Switzer (English), 1729; Arago, 1835; Dumas, 1856; Keilhack, 1912. The dates of two of the books are deceptive in so far as their reviews of the opinions of their predecessors are concerned, for both Dumas and Keilhack base their reviews of the opinions of others on Perrault. Dumas surveys three other later opinions, besides having a chapter in which he essays to review the theory in a complete manner. In these four reviews the original language of the several earlier writers is seldom given, and then generally in fragments.

Thales, one of the earliest and most notable of the Greek philosophers (6th century B.C.), left no writings. Diogenes Laertes, to whom we are indebted for fragments and three letters of Thales, reports nothing by Thales on springs. Keilhack says that Thales "was of the opinion that the water of springs and streams is derived from the sea--driven out--into the Earth by the wind and when once in the Earth it was forced out again in the mountains by the pressure due to gravitation of the overlying rocks."

Pythagoras (born about 580 B.C.) also left no writings. The Pythagorean philosophy as detailed long after the death of the founder by Ovid in his "Metamorphoses" (about 1 B.C.) details the evaporation-condensation theory, but does not mention springs. After mentioning the four elements Ovid writes:

> All things are mixed of these, which all contain,
> And into these are all resolved again:
> Earth rarefies to dew; expanded more
> The subtle dew in air begins to soar.
> . . . . . .
> And dew condensing, does her form forego,
> And sinks a heavy lump of Earth below.
> . . . . . .
> Thus are their figures never at a stand,
> But changed by Nature's innovating hand;
> All things are altered, nothing is destroyed,
> The shifted scene for some new show employed.

Plato must be passed over as merely putting into the mouth of Socrates, a few hours before his death by the hemlock (399 B.C.), a theory of the Earth and its waters which Socrates says is easier to describe than defend. It deals largely with Tartarus and is similar to the Mosaic Abyss and the four rivers flowing out from Eden. Although no mention is made of springs, the myth is sometimes cited as classing Plato with the ocean-fed theorists.

The great philosopher Aristotle (384-322 B.C.), who wrote the first book to bear the name Meteorology, was the first writer to attempt a complete scientific account of the origin of springs and rivers. He held that both come from the condensation of moisture--the one from above the other from within the Earth. Let us now have Aristotle's own words under the headings "Sources of rains" and "Sources of rivers," bearing in mind that, although he wrote about the formation of springs, he had no such heading. First, as to rivers:

"[The region] which immediately surrounds the Earth [is] common to water and air, and the processes attending the formation of water above take place in it. The efficient and chief and first cause [of the formation of water] is the circle in which the Sun moves . . . the Earth remains but the moisture surrounding it is made to evaporate by the Sun's rays and the other heat from above, and rises. But when the heat which raises it leaves it, in part dispersing to the higher region, in part quenched through rising so far into the upper air, then the vapor cools because its heat is gone and because the place is cold, and condenses again and turns from air into water. And after the water has formed it falls down again to Earth. . . . So the moisture is always raised by the heat and descends to the Earth when it gets cold again. . . . When water falls in small drops it is called a drizzle; when the drops are larger it is rain." (Book I, Chap. IX, 346 b.)

Under "Origin of rivers" Aristotle first cites the subterranean-reservoir theory held by some others:

"It is thought [by some] that the water is raised by the Sun and descends in rain and gathers below the Earth and so flows from a great reservoir, all the rivers from one, or each from a different one. No water at all is generated, but the volume of the rivers consists of the water that is gathered into such reservoirs in winter. Hence rivers are always fuller in winter than in summer, and some are perennial, others not. . ."

He disposes of this in a sentence:

"But if any one will picture to himself a reservoir adequate to the water that is continuously flowing by day and consider the amount of water, it is obvious that a receptacle that is to contain all the water that flows in a year would be larger than the Earth, or at any rate not much smaller."

Next comes Aristotle's back-handed remark to the effect that water is condensed from within as well as outside the Earth, but with no mention of its being stored in underground reservoirs:

"Though it is evident that many reservoirs of this kind do exist in many parts of the Earth, yet it is unreasonable for any one to refuse to admit that air becomes water in the Earth for the same reason as it does above it. If the cold causes the vaporous air to condense into water above the Earth we must suppose the cold air in the Earth to produce this same effect, and recognize that there not only exists in it and flows out of it actually formed water, but that water is continually forming in it too."

In what follows Aristotle again denies that rivers flow from subterranean reservoirs, tells in effect how springs head underground and feed rivers, particularly in the mountains, and again denies that rivers "originate in definite reservoirs":

"Again, even in the case of the water that is not being formed from day to day but exists as such, we must not suppose as some do that rivers have their source in definite subterranean lakes. On the contrary, just as above the Earth small drops form and these others, till finally the water descends in a body as rain, so too must we suppose that in the Earth the water at first trickles together little by little, and that the sources of the rivers drip, as it were, out of the Earth and then unite. This is proved by facts. When men construct an aqueduct they collect the water in pipes and trenches, as if the Earth in the higher ground were sweating the water out. Hence, too, the headwaters of rivers are found to flow from mountains, and from the greatest mountains there flow the most numerous and greatest rivers. Again, most springs are in the neighborhood of mountains and high ground, whereas if we except rivers, water rarely appears in the plains. For mountains and high ground, suspended over the country like a saturated sponge, make the water ooze out and trickle together in minute quantities in many places. . . . . It is clear then that we must not suppose rivers to originate in definite reservoirs." (Book I, Chap. XIII, 349 b.)

In his exposition of the Epicurean Philosophy called "De Natura Rerum" the poet Lucretius (about 99-55 B.C.) gives a clearer exposition of the forces of Nature engaged in the pluvial cycle than did Aristotle in his "Meteorology." A notable feature of Lucretius' poem is the passage in which he raises and answers the question why does the ocean which receives all the rivers, not overflow. The answer, from Creech's rhymed translation of the seventeenth century, is:

The Sun drinks some, to quench his natural heat;
And some the winds brush off. . . .

Some passes through the Earth, diffused all o'er,
And leaves its salt behind in every pore;
For all returns thro narrow channels freed
And Joyns where e're fountain shows her head;
And thence fine streams in fair Meadows play.

In his more specific account of the origin and circulation of waters Lucretius first describes the formation of clouds and rain. Clouds begin with the combination of "many particles of rougher kind." These are driven together by winds, added to from below by rising mists and compressed from above by "emanations from the starry ether" until "a wet of clouds" is formed "beneath the blue." These and other "first beginnings" result in "storm and darkness hanging from above."

On rain or the discharge of "seeds of water" the poet says, quoting now from Jackson's rhythmic prose translation:

> ". . . . When the winds bear clouds, hanging like woolen fleeces, over the great sea, they often gather much sea-water. In a like way moisture is taken up into the clouds from the rivers. . . the winds' force thrusts them [clouds] in collision . . . . and makes showers flow out . . . . [and sometimes there are heavy rains]."

Toward the end of this section Lucretius says that sea-water oozes into adjacent porous soil, is sweetened and oozes back again, "converging to the river-head." After this it pours once more "o'er the lands." He enlarges upon an idea previously expressed, implying an ocean-fed theory, kept secondary to the pluvial origin of springs.

The first engineer to describe the origin of springs was the Roman, Vitruvius. This he did in the eighth of his "Ten books of architecture" written about 15 B.C. In essence he was in accord but in detail he was clearer and more specific than either Aristotle or Lucretius in their pluvial theories. Besides he brought in the idea of Earth's strata affecting springs.

Vitruvius was treating primarily of sources and quality of water-supplies. Taking out and arranging in logical order what he wrote on evaporation and condensation, precipitation and springs, we have the following:

> [Evaporation and condensation] That vapor and mists and humidity come from the Earth, seems due to the reason that it contains burning heat, mighty currents of air, and a great quantity of water. So soon as the Earth, which has cooled off during the night, is struck by the rays of the Sun, and the winds begin to blow while it is yet quite dark, mists begin to rise upward from damp places. . . .
>
> [Precipitation] Whenever the winds carry the vapor which rolls in masses from springs, rivers, and marshes and the sea it is brought together by the heat of the Sun, drawn off, and carried upward in the form of clouds: Then the clouds are supported by the current of air until they come to the mountains where they are broken up from the shock of collision and the gales, turn into water on account of their fullness and weight and in that form are dispersed upon the Earth (as rain). . . .
>
> [Springs] The valleys among the mountains receive the rain most abundantly, and on account of the thick woods, the snow is kept in them longer by the shade of trees and mountains. Afterwards, in melting, it filters through the fissures in the ground and thus reaches the very foot of the mountains, from which gushing springs come belching out.
>
> But in flat countries, on the contrary, a good supply cannot be had. For however great it is it cannot be wholesome, because as there is no shade in the way, the intense force of the Sun draws up and carries off the moisture from the flat plains with its heat, and if any water shows itself there, the lightest and the purest and the delicately wholesome part is summoned away by the air, and dispersed to the skies, while the heaviest and the hard and unpleasant parts are left in springs that are in flat places.

Quite incidentally Vitruvius mentions deep-seated waters and Earth strata. Nowhere does he show a conception of the existence and functions of permeable and impermeable inclined strata, in the origin and movement of underground waters.

Hot springs, Vitruvius says, are brought to the surface by heat and entrained air. He adds:

"When such springs are not opened but confined by rocks, the force of the air in them drives them up through the narrow fissures to the summits of the hills [italics mine]. as long [as such springs] are confined to narrow channels, the currents of air in the water run up in bubbles to the top, but as soon as they are given wider outlets, they lose their air on account of the rarity peculiar to water, and so settle down and resume their proper level."

Coming near the end of the classical period and the beginning of extensive reviews of theories as to the origin of springs, we find the third of Seneca's seven books on natural history ("Questions Naturalis") (63 or 64 A.D.) devoted to "Forms of water" including the circulation of water on and in the Earth. The review scarcely mentions the pluvial theory. Seneca's belief was that condensed internal vapors fed springs. Rainfall, he declared, cannot possibly be the source of springs because it penetrates only a few feet into the Earth whereas springs are fed from deep down. As to the former Seneca declared: "As a diligent digger among my vines I can affirm my observation that no rain is ever so heavy as to wet the ground to a depth of more than ten feet." This assertion seems to have been undisputed for centuries with curtailments by some to two feet.

After Seneca there was an almost unbroken silence on the origin of springs until the sixteenth century. When the voices again became active, it was for the most part only to revive one or other of the old theories, often with interesting variations in detail and sometimes with fantastic embellishment. Now and then there were refreshing contributions of new physical data from visual inspection of rivers, brooks, and springs, and from crude rain-gages.

One of the most fantastic embellishments was embodied by the astronomer, Kepler, in his "Harmonices Mundi" (1619). According to Keilhack, the astronomer said "that the Earth forever drinks in water from the sea, like a great beast, digests and assimilates it in its body" adding that "ground-water and springs are the end-products of the Earth's metabolism."

A century later Athanasius Kircher, in his "Mundus Subterraneous" (1717), advanced a theory, illustrated by a diagram, in which he assumed "Hydrophylacia" and "Pyrophylacia" or water and fire caverns (prisons) in the crust of the Earth, fed respectively by the sea and a great fiery mass at the center of the Earth. The first of these, with the aid of heat, causes springs; the second gives rise to volcanoes. Keilhack says that Kircher's general idea as to volcanic action is in line with "the most modern of all theories of volcanic action, that of Stubel."

Mariotte in his book of 1686 restated with improvements the pluvial theory of the origin of springs, refuting the ocean-fed theories and the claims that rainfall penetrates only a few feet into the ground. His great contribution to hydrology was his rainfall-measurements, the application of the results to the computation of the relation between rainfall and runoff, and his conclusions that rainfall is sufficient to feed springs and rivers.

Unlike Kepler, the earlier astronomer, Halley, of comet and other fame, added materially to the knowledge of water-circulation. In 1693 he reported to the Royal Society results of studies he had some time earlier been instructed to make on how much water is evaporated from the sea in a day and Nature's method of returning that vapor to the sea. His conclusion, supporting the pluvial origin of springs, was not so remarkable as the fact that he made an extended study of the subject. Among his supporting data were observations of vapors and their condensation while he was on an astronomical mission to St. Helena. One of his general conclusions was that winds carry vapors to mountain tops where they precipitate, "gleeting down by the crannies of the stone" and finally breaking out by the "sides of the hills" as "single springs." More important was a conclusion on what we would now call the runoff of streams. He wrote: "And it may almost pass for a rule that the magnitude of a river or the quantity of water it evacuates is proportional to the length and the height of the ridges from which its fountains arise." Although lacking several factors recognized later, this showed progress in knowledge.

In 1660 John Ray delivered two series of sermons which contained germs of two books which he published nearly at the close of the century. Ray describes a brook flowing close by his dwelling. This he had ascended to its source, noting that it was fed by numerous rivulets along the way and by a spring at the top which in turn must be supplied with water from adjacent ground. All this water evidently came from rain. Applying these observations to several large European rivers whose courses he had inspected, he wrote that they "did not seem to him to bear any greater proportion to the rivers and rivulets they receive and the immense tracts of land that fed them than my small brook doth to its small rills and compass of ground." This is in line with the rule of Halley already given.

Bare mention can be made in passing to the French popular scientist, Pluche, who in his

"Spectacle de la Nature" (1732) took the youth he was instructing to the outcrops of strata in the city of Laon on the upper part of the mountain of the same name, and to springs from lower outcroppings of the same strata. In this way Pluche visualized the pluvial origin of springs.

At the close of the eighteenth century Erasmus Darwin, grandfather of Charles, and partial anticipator of the latter's "Origin of species," made practical use of his knowledge of exposed inclined strata to rejuvenate a bad well by sinking one within it to a stratum that he knew outcropped at a higher level. He also described the origin of springs in his poem the "Botanic Garden" and in his prose work "Phytologia."

Into the nineteenth and twentieth centuries, with their development of geological and hydrological knowledge and scientific data, and their use to provide water for potable and industrial purposes, it is not the intent of this paper to enter.

[Note--The preceding paper has been prepared from original sources or at least from the earliest available transcripts of such sources. Views of modern authors regarding the precise meaning of some of the earliest writers do not always agree. The reader may find it interesting to compare the preceding paper with two other recent notable accounts of the historical development of the theories on the origin of ground-water: (1) The history and development of ground-water hydrology, by O. E. Meinzer, J. Wash. Acad. Sci., v. 24, No. 1, Jan. 15, 1934; and (2) The origin of springs and rivers--an historical review, by F. D. Adams, Fennia 50, No. 1, Helsingfors, Finland, 1928 (abstract in Geol. Soc. Amer. Bull. 39, pp. 149-150, 1928, and note on Rainfall and runoff in Science, v. 67, pp. 500-501, 1928.]

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Upper Montclair, New Jersey (MNB)
Voorheesville, New York (REH)

## SEVERAL METHODS OF STUDYING FLUCTUATIONS OF GROUND-WATER LEVELS

Leland K. Wenzel
(Published with the approval of the Director, U. S. Geological Survey)

As a result of increased interest in ground-water conditions in recent years, records of water-levels in wells are now being collected in many places in the United States for the primary purpose of determining the relation of precipitation and other natural factors to fluctuations in water-level. In the past, records of ground-water levels have been collected chiefly in connection with intensive investigations in areas where the water-levels were affected by artificial withdrawals and it has not been generally possible to correlate water-level fluctuations closely with natural factors. It now appears probable that certain methods of studying water-level fluctuations may be utilized advantageously in areas unaffected by heavy artificial withdrawals, but these methods generally do not yield satisfactory results in areas where there is considerable pumping or artesian flow. Three such methods are presented in this paper. The methods have not been given intensive study and their practical use is therefore not yet fully known. It is hoped that their application will be further investigated. Illustrations of the