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9

The seventeenth century

INTRODUCTION

Very often historians call the seventeenth century 'the cradle of modern science', because it started with so little knowledge and ended with so much. It made impressive and significant contributions such as Galileo's mechanics, Kepler and Newton's astronomy, Harvey's blood circulation, Descartes' geometry, Van Leeuwenhoek and Hooke's microscopy, and last but not least, Perrault, Mariotte and Halley's experimental investigations which produced a concept of the hydrologic cycle. This was the period that saw the downfall of Aristotle, and the remoulding of man's mind, by replacing the teleological aspects of the previous centuries with experimental philosophy. John Dryden (1631–1700) in his poem *Longest tyranny*, written in 1663, the year of his election to the Royal Society, said:

'The longest Tyranny that ever sway'd
Was that wherein our Ancestors betray'd
Their free-born *Reason* to the *Stagirite*
And made his *Torch* their universal *Night*.
So Truth, while only *One* supplies the State,
Grew scarce, and dear, and yet sophisticate[*];
Until 'twas bought, like Empirique Wares, or charms,
Hard words sealed up with Aristotle's Armes[**].'

Aristotle thought that 'all men by nature desire to know', but it took Johannes Kepler and some two thousand years to state that 'to measure is to know'. According to Francis Bacon (1561–1626):

'There are two ways, and can only be two of seeking and finding truth. The one, from sense and reason, takes a flight to the most general axioms, and from these principles and their truth, settled once for all, invents and judges of all intermediate axioms. The other method collects axioms from sense and particulars, ascending continuously and by degrees so that in the end it arrives at the most general axioms. This latter is the only true one, but never hitherto tried.'[1]

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[*]In the seventeenth century English, sophisticate meant adulterated.
[**]The last two lines mean that obscure and dubious works were made significant by just being attributed to the authority of Aristotle, the great master.

The various developments in the field of hydrology during the seventeenth century are discussed herein, except those of Pierre Perrault, Edmé Mariotte, and Edmond Halley. They will be treated separately in the next chapter.

GALILEO, KEPLER AND DESCARTES

Galileo Galilei (1564–1642) started his life with the traditional scholastic teaching of Aristotelean theories, but he soon abandoned them. In 1585, he started to conduct experimental investigations with some of Aristotle's doctrines and, by 1590, proved that some of them were wrong. Galileo did not contribute much to the development of hydrology directly, but his attitude towards science had a profound effect on all branches of knowledge, and hydrology was no exception. Both Benedetto Castelli and Evangelista Torricelli, his students, were considerably influenced by this Italian polymath.

The German, Johannes Kepler (1571–1630), a contemporary of Galileo and a man of strong mystical tendencies, was the real founder of scientific heliocentrism.[2] His work was responsible, to a certain extent, for the downfall of Ptolemy; just as Galileo's experiments helped destroy the reputation of Aristotle. His idea of the universe was somewhat Platonic and Pythagorean. During the early seventeenth century, the concept that the earth is a living being or at least it functions like one, gained some supporters, including Kepler. Adherents of this principle could be found even as late as the nineteenth century. The theory can be seen in Kepler's, *Harmonices mundi*, published in 1619, which dealt with his third and the last great law of the planetary motion. According to it:

> 'The globe contains a circulating vital fluid. A process of assimilation goes on in it as well as in animated bodies. Every particle of it is alive. It possesses instinct and volition even to the most elementary of its molecules, which attract and repel each other according to sympathies and antipathies. Each kind of mineral substance is capable of converting immense masses of matter into its own peculiar nature, as we convert our aliment into flesh and blood. The mountains are the respiratory organs of the globe, and the schists its organ of secretion. By the latter it decomposes the waters of the sea, in order to produce volcanic eruptions. The veins in strata are the caries or abscesses of the mineral kingdom, and the metals are products of rottenness and disease to which it is owing that almost all of them have so bad a smell.'[3]

The earth drinks in sea-water which undergoes the process of digestion and assimilation, and the end product of these physiological processes is discharged through springs.[4, 5]

René Descartes (figure 1), son of a lawyer, was born at La Haye in Touraine, in 1596. He was educated at the Jesuit College at La Fleche, in Anjou, and later at the University of Poitiers from where he graduated in Law, in 1616. He travelled extensively in Europe and came to know people like Mersenne and Picot. In 1628, he discarded his nomadic life in favour of working to establish a new philosophy, free from the influences of ancient doctrines. He went to Holland to carry out his studies in tranquility (because the country was peaceful) under the Stadholder, Prince Frederic Henri, who had a reputation for encouraging religious freedom, which was rather unusual for that time. The book *Discours de la méthode* (Discourse on method) with three accompanying essays, *La dioptrique* (Dioptrics), *Les météores* (Meteors), and *La géométrie* (Geometry) was published in 1637. He died in Stockholm, in 1650.

Figure 1. René Descartes (by courtesy of the Royal Society of London).

Descartes, like Herodotus and Bacon, considered all knowledge to be within his province, but mathematics was the particular subject in which he found real satisfaction. The major work, so far as hydrology is concerned, is his essay on meteors. He attempted to attribute natural causes to natural phenomena, and even though his reasoning was not always correct, he at least separated them from the realm of magic and occult.

Les météores is probably the most original work on the subject since Aristotle's *Meteorologica* and, in it, Descartes tried to explain various meteorological phenomena on a 'scientific' basis. It is true that the work does not reach the same high standards as his writings on mathematics or even optics but, nevertheless, it is quite a significant piece of writing. He believed that one needs to know about the structures of air, water, and the earth, as well as the bodies on it, to understand various natural phenomena. They are composed of infinite numbers of little parts of different sizes and shapes which, as they are not compactly joined, have gaps in between them, filled with a fine 'subtle matter'. The component parts of water are long and smooth, and can be easily separated as they never get hooked together. In contrast to water, air, and other bodies, have very irregular components. If there are many gaps around the constituents that are filled with the subtle matter, the material becomes very rare and light, like air or oils.

Even the formation of ice and expansion of water while freezing were explained by the presence of the subtle matter. Descartes, however, did believe some ‘old wives’ tales:

‘And we see by experience that water which has been kept on a fire for some time freezes more quickly than otherwise; the reason being that those of its parts which can be most easily folded and bent are driven off during the heating, leaving only those which are rigid.’[6]

Had he conducted a simple experiment, he would have undoubtedly found out the truth about this medieval concept, but it indicates that Descartes was not entirely free from relying on *a priori* conclusions.

He explained the process of evaporation by the presence of the subtle matters which are agitated by the sun or some other cause. The subtle matters, in turn, agitate the bodies which envelop them. The smallest parts become detached and rise up – not because of their natural tendency or even the attraction of the sun but due to their motion that cannot continue in any other direction. The land and sea breezes are caused by the expansion of vapours, as they have a tendency to move to those regions where they can find more space. Clouds and fogs are formed when the expanded vapours condense and become more compact. As the vapour particles get chilled they lose their mobility – thus forming water droplets or ice crystals. Since for a given volume a sphere has the least surface area, water droplets generally become spherical. Their shapes might become changed because of the influence of other forces, i.e., air resistance during rainfall. A single droplet remains suspended in the air but when a few of them combine, their total weight becomes too great, and they consequently fall either as rain or dew.

The formation of snow or hail was explained in a different manner. Snowflakes, which are frozen and expanded water, are light and do not generally fall to the earth. But sometimes, because of certain conditions like the expansion of air above the clouds, they do come down. If they are melted completely by warm air while falling, rainfall occurs; but if they remain unmelted snowfall; while if, after having melted, they meet cold wind, hail is produced.

Descartes’ concept on the origin of springs and rivers was curious, to say the least, but his theory was the dominant one for nearly two centuries. He maintained that the sea-water diffuses through a series of subterranean channels, in various directions, until it reaches large caverns at the base of a mountain. There the water evaporates due to the heat of the earth's interior, and the salt is left behind (because it is too ‘gross’ and heavy). The vapour is subsequently condensed by the low temperature at the top of the vaults, and the water produced there emerges as streamflow.[7–9] Curiously, nowhere does he mention what happens to the enormous deposit of salt that would have accumulated if his theory had been true.

Probably Les *météores'* greatest claim to fame is the section on rainbows which is exhaustive and extremely well-written, but it does not have any direct connection to the science of hydrology.

CASTELLI ON DISCHARGE CALCULATIONS

Benedetto Castelli (1577–1644; figure 2), born at Brescia, was entered into the Benedictine monastery of Montecassino at an early age. The Montecassino, as it may be recalled, had already ascertained a unique place in the history of hydrology by preserving the irreplaceable work of Frontinus for posterity. Castelli was a student of Galileo and later became one of his most trusted friends' When Galileo's theories on hydrostatics were attacked, he vigorously defended them.

Castelli, a mathematician to the Pope Urban VIII, taught mathematics at the universities of Rome and Pisa. In the preface of the book *Della misura dell'acque correnti*,[10] published in 1628, Castelli stated that he was ordered by the Pope to apply his thoughts to the motion of water in rivers – a subject which is difficult, most important and very little considered by others. His teacher Galileo once said that 'I can learn more of the movement of Jupiter's satellites than I can of the flow of a stream of water',[11] and no wonder, when Castelli's work was published, it was proclaimed by his teacher to be a 'golden book'.

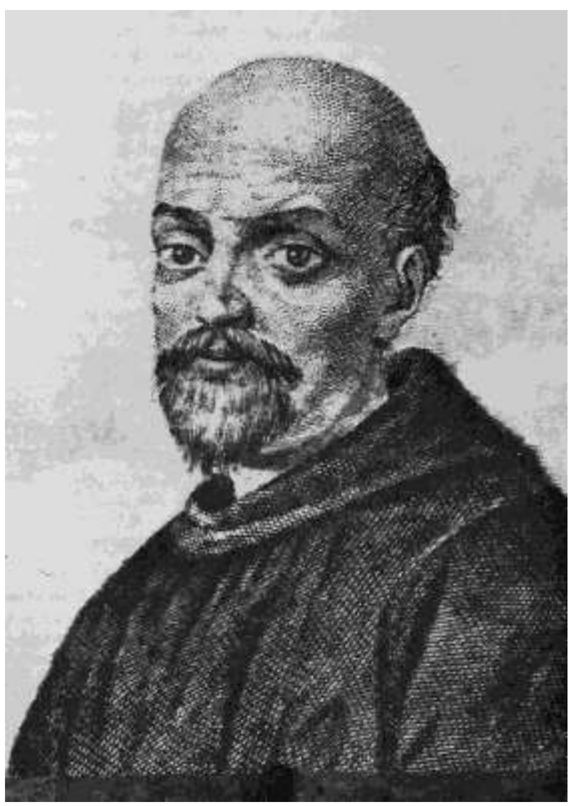

Figure 2. Benedetto Castelli

The main contribution of the Benedictine monk to hydrology is his clear explanation of the relationship between velocity and discharge of flow, a concept put forward by both Hero and Leonardo, but in those instances, had gone completely unnoticed. The book[10] restated the principle of continuity most convincingly and, for that reason, he is often called the father of the Italian school of hydraulics. The principle, as suggested by Castelli, was that:

'... in divers parts of the same river or current of running water, there doth always passeth equal quantity of water in equal time and it being also true, that in divers parts the same river may have various different velocity; it follows of necessary consequence, that where the river hath less velocity, it shall be of greater measure, and in those parts in which it hath greater velocity, it shall be of less measure; and in sum, the velocity of several parts of the said river, shall have eternally reciprocal and like proportion with their measures.'[12]

From the above theory, he derived five axioms. They are:

Axiom I: 'Sections equal, and equally swift, discharge equal quantities of water in equal times.'

Axiom II: 'Sections equally swift, and that discharge equal quantity of water, in equal time, shall be equal.'

Axiom III: 'Sections equal, and that discharge equal quantities of water in equal times, shall be equally swift.'

Axiom IV. 'When sections are unequal, but equally swift, the quantity of the water that passeth through the first section, shall have the same proportion to the quantity that passeth through the second section. Which is manifest, because the velocity being the same, the difference of the water that passeth shall be according to the difference of the sections.'

Axiom V. 'If the sections shall be equal, and of unequal velocity, the quantity of the water that passeth through the first, shall have the same proportion to that which passeth through the second, that the velocity of the first section, shall have to the velocity of the second section. Which also is manifest, because the sections being equal, the difference of the water which passeth, dependeth on the velocity'.[13]

He vigorously criticized[14] Fontana's work[15] on floods because of the erroneous '*Q=A*' concept. He pointed out that since Fontana had completely neglected the velocity of flow, the recommendation of widening the river channel could not be correct.

The originality of Castelli is extremely difficult to ascertain as it is quite possible that he was familiar with the Vatican Compilation of Leonardo's notes and, thus, may have been deeply influenced by it[16]. It is certainly remarkable, as will be seen in the next subsection, that he made the same mistake as Leonardo on the efflux problem, but that really does not prove anything. Lombardini,[17] for example, considered it to be ‘an exceedingly unpleasant task’ to expose Castelli as a plagiarist. He concluded that:

> ‘... the hydraulic science was without a doubt created by Leonardo, but that in truth, the engineers of Lombardy were unable to consult and profit by his writings until about 1570, because the various proposition had become so scattered, and were expounded in such a way that it was difficult to read them. Castelli must have become acquainted with them 60 or 70 years later, although he maintained that he had deduced by experiments, propositions which in form and terminology, appear to have been obtained directly from the writings of Leonardo.’[18]

Poggendorff, on the other hand, considered[19] Castelli’s book to be the first containing correct principles of flow of water in rivers and canals. Since it is possible that Castelli was wholly independent of Leonardo’s influence, he should not, in all fairness, be called a plagiarist – at least not until some convincing evidence has been found. Be that as it may, no one would deny that he has done a great service to the science of hydrology by the much-needed correction in the discharge formula.

Castelli also made the first rain gauge in Europe, but more about that will be discussed in chapter 2.

THE EFFLUX PRINCIPLE

It was known, at least vaguely, from the time of Frontinus that the quantity of water flowing outward through an orifice at the bottom of a vessel was relates to the head of water which exists above such an orifice. The problem was still not completely solved until the beginning of the seventeenth century. Galileo, in course of his experiments, for example used to measure time by the relative weights of water discharged from a large bowl of water with an orifice in its bottom. He and his son had both tried to build a water block, but because of the error in that concept, their ventures failed to succeed. Probably Castelli’s interest in the efflux problem was aroused by his master's makeshift water clock but he did not make much progress thereon. It was his belief that velocity depended directly on the height of water. In all fairness, however, it should be pointed out that he was not happy with this belief The problem was first solved by Evangelista Torricelli (1608–1647) who is sometimes credited with the invention of the barometer.[20] It was Torricelli, who first stated that the velocity of efflux is dependent on the square root of the head. The deterministic equation $v = \sqrt{2gh}$, however, was not actually written until about 1738. The value of g, which was determined by Christian Huygens (1629–1695) in 1673, first had to be evaluated, and as a matter of fact, that equation was not expressed until the two Bernoullis did so in 1748. Among others who worked theoretically and experimentally, on the development of the velocity formula were Maggiotti, MacLaurin, Poleni, Newton, Guglielmini, Grandi, Mariotte and Michelotti. Frisi has admirably summed up[2l, 22] the development of the efflux principle to about the middle of the eighteenth century.

ATHANASIUS KIRCHER

The German Jesuit, Athanasius Kircher (1602–1680; figure 3), was a professor at Würtzburg, who wrote a number of bulky treatises on many subjects. The book *Magnes, sive de arte magnetica* was published in Rome in 1641, and his most important work on the subterranean world[23] *Mundus subterraneus*, came out in 1664. Both the books indicate that Kircher had an extremely fertile imagination, so much so that the book on magnetism had a separate section on the magnetism of love. The other book deals with everything within the earth, including the origin of springs and rivers. *Mundus subterraneus* became a standard geology textbook in the seventeenth century.[24] On the subject of the origin of rivers and springs Kircher was unable to free himself completely from the centuries-old domination of the Church. He started with the fundamental concept from *Ecclesiastes*, namely that rivers receive their supply of water from the sea. He considered Aristotle’s concept of transformation of air into water to be rather ludicrous. He, however, used part of the Stagirite's idea for promoting his own concept. He thought that there are many great hydrophylacia (caverns containing water) within the major mountain ranges of the world, and that they were formed by God in his great wisdom during the creation of the world. Rivers flow out of these caverns in various parts of the world in order that man can use them either for irrigation or navigation.

Since the quantity of water in a hydrophylacium is not limitless (as stated in Plato’s Tartarus), he had to seek another explanation for their sources of supply. He soon found it in a verse from *Ecclesiastes*. There were two major problems or rather handicaps for the Jesuit to surmount, and one must give him credit for identifying them, even though his explanations were wrong. This is much better than some of his more illustrious predecessors who did not even recognize them. The difficulties lie in the nature of the connections between the hydrophylacia and the sea, and in the problem of raising sea-water to a higher level than it was originally. Kircher believed that such difficulties could be overcome, saying that ‘there is no man with mind so dull, as not to be ready to follow on hands and fact, as the saying is, my trains of thought’.[23] Solving the first problem was comparatively easy, as he visualized sea-water passing to a hydrophylacium through openings in the ocean-floor. Figure 4 is an idealized sketch of a mountainous area near the sea. The whirlpools in the figure indicate the locations of openings in the sea-bed through which water is carried by subterranean channels to the caverns of mountains from where the rivers originate. The water is returned to the sea by the rivers, thus completing his version of the hydrologic cycle. In the diagram, the subterranean channels appear in a darker shade whereas the rivers are shown in a lighter shade. Figure 5 represents a section of a mountain with a cavern being supplied through subterranean channels with water from the sea.

Figure 3. Athanasius Kircher.

Figure 4. Kircher’s explanation of the origin of rivers and springs.

Figure 5. Kircher's view of a cavern being supplied with sea-water.

Various theoretical processes for getting water to flow uphill (from the sea to mountain tops) by mechanical methods were explained with elaborate diagrams. A brief discussion of three of those processes is presented here. The first contemplated the use of a pair of double bellows powered by water-wheels to raise the water, and the second, a U-tube filled with water, which had one limb shorter than the other. The opening of the shorter limb was to be covered with a flexible diaphragm. When pressed, it would raise the water in the other arm higher than it was originally. The third contemplated water being raised by the creation of a vacuum. Kircher experimented with all those methods to assure himself that they would work. Having done that, he searched for an analogous process in nature, and finally arrived at an answer with which he was satisfied. It was that tides, which are created in the sea by the attraction of the moon, would cause one mass of water to acquire a higher level than the other. This condition would produce the necessary pressure, as could be demonstrated by his U-tube experiment. This provided the justification he needed to claim that sea-water is forced through the openings in the bed, and that it flows under pressure to the mountain tops. High winds contributed a share of the pressure on the ocean surface, and they helped to force water through the subterranean channels created by God in his divine wisdom (just like the veins and arteries in the body of man, the microcosmos, to accomplish the purposes for which they were created).

A second method by which sea-water could be raised to higher than its original level was claimed to be produced by the action of fire. Kircher believed that the underground world is:

‘a well fram’d house with distinct rooms, cellars, and store-houses, by great art and wisdom fitted together; and not as many think, a confused and jumbled heap or chaos of things, as it were, of stones, bricks, wood, and other materials, as the rubbish of a decayed house, or a house not yet made.’[25]

The caverns are occupied by either fire or water, and all the fire-filled ones have a direct communication with the central fire. If the fire is near the surface, it could break out as a volcano, but if it is located deeply within the earth, it heats up the water in a nearby cavern, assuming, of course, that such a cavern exists. The water vapourizes, comes towards the surface, recondenses, and thus generates hot springs. Figure 6 shows a hot and a cold spring with origins close to one another. The explanation was very simple: the hot spring A is created by the passage of the subterranean channel L over the fire-filled cavern S, whereas the spring B is cold as there is no fire nearby. If, after being heated as in the case of spring A, water has to travel a long distance before it comes to the surface, cooling takes place and a cold spring is produced.

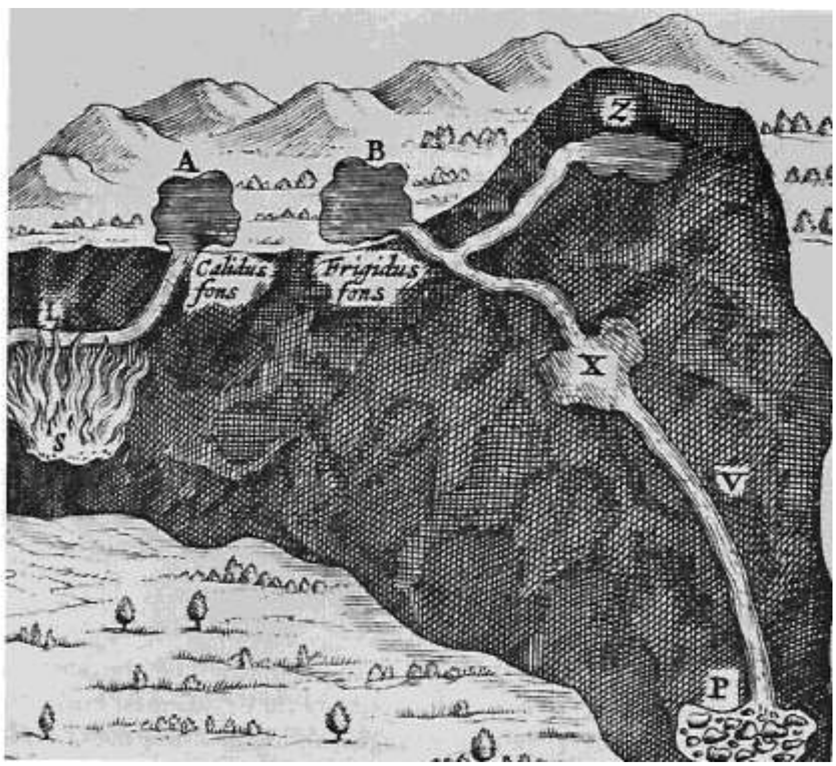

Figure 6. Origin of hot and cold springs according to Kircher.

Formation of mineral springs is shown in figure 7. Issuing from a common hydrophylacium A, the water qualities of the springs change according to the mineral substances they encounter enroute. For example, spring H passes through sulphur-bearing rocks and, hence, it is sulphurous, whereas the water from spring B is pure because it does not pass through any soluble materials.

It is evident that Kircher was deeply interested in groundwater and origin of springs and rivers but, unfortunately, his basic concepts were not correct.

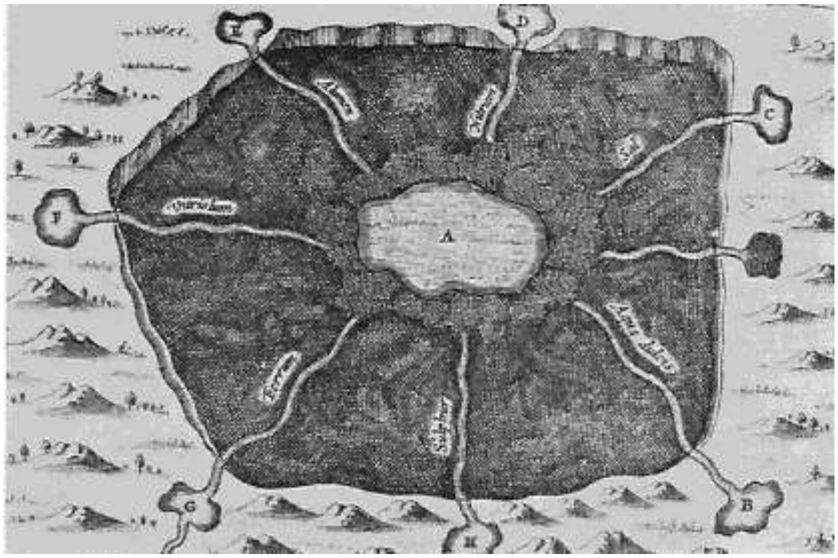

Figure 7. Kircher's explanation of formation of mineral springs.

SCHOTT AND BECHER

An abridged version of Kircher's views was first published in 1656.[26] Three years later, another Jesuit, Gaspard Schott (1608–1666), treated the subject of rivers and springs rather exhaustively. He disagreed with Kircher, and interpreted the verse from *Ecclesiastes* to suit his own purposes:

'We are of the opinion that some springs and rivers have their origin from subterranean air and vapours which have been condenses into water. Others from rain and snow which have soaked into the earth, the greatest number and the most important rivers, however, from sea water rising through subterranean passages and issuing as springs which flow continuously. And so the sea is not the only source, at least it does not distribute its water through underground passages to all these springs and rivers. But this statement would seem to run contrary to the clear teaching of Holy Writ found in Ecclesiastes, chapter 1 and verse 7, *All rivers run to the sea*; *yet the sea is not fully unto the place whence the rivers come, thither they return again*. The real meaning of these words however seems to be: Ali rivers run into the sea, from the place out of which they come, to it they flow back again. Consequently those which enter the sea have issued from the sea, and those which have issued from the sea return to it and enter it that they may flow out of it again. But all enter it and all return to it, therefore all have issued from it. But it does not follow that some, as we believe, have not come out of the sea by another road than that just mentioned. I am, therefore firmly of the opinion and again repeat, all rivers do not issue from the sea – at least alt do not make their exit directly out of the ocean into the depths of the earth and from there rise through subterranean channels to their fountain heads. This is held to be true not only by recent authorities as, 'Conimbricensium' Fromondus, Cabeus, Cornelius, Magnanus, as seen in their words above referred to, but also by Albertus Magnus, (Duns) Scotus and a multitude of others who believed it to be consonant with the teaching of Scripture.'[27, 28]

Johann Joachim Becher (1635–1682) was one of the most well-known alchemists of the seventeenth century. He believed that there was a large vaulted space in the centre of the earth which was extremely hot due to the ignition of sulphurous and bituminous materials. The water from the sea comes to the fiery centre through various fissures, and then evaporates. The vapour rises through the earth's crust to the tops of mountains where it condenses and gives rise to springs and rivers.[29] Thus, Becher's theory was somewhat similar to that of Descartes: the only difference is that the alchemist believed that water evaporated at the centre of the earth whereas Descartes believed that evaporation took place in caverns located at the base of mountains. These basic concepts, quite common during the sixteenth and the seventeenth centuries, all show a similarity to the working of an alembic (figure 8). Before the idea had been conceived, it had been commonly believed that salt water, during its travel, passed through fissures that were so narrow that only pure water could pass through them and that the salt was left behind. When it was realized that salt can be separated from sea -water only by distillation (and not by filtration), the new alembic theory began to receive popular acceptance.

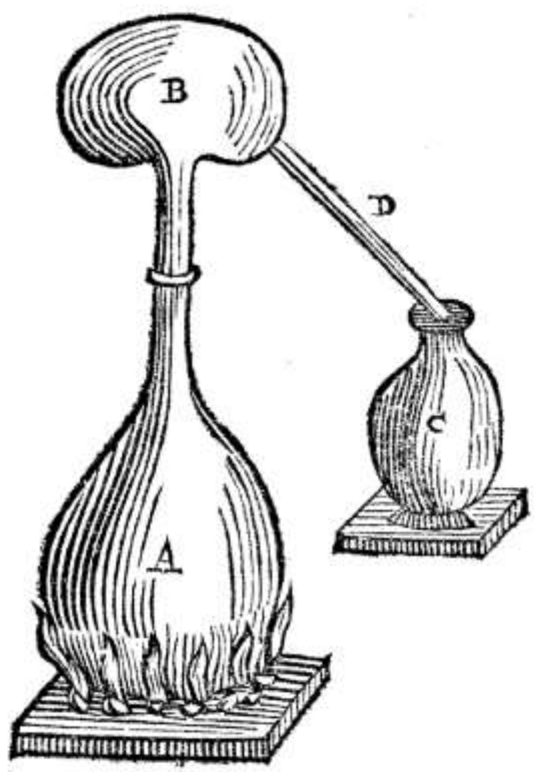

Figure 8. An Alembic.

BERNHARDUS VARENIUS

Bernhardus Varenius (1622–1650), born in Hanover, was trained in medicine at Königsberg and Leyden. He settled in Amsterdam and wrote two books, *Descripto regni Japonise and Geographia generalis*, which were published in 1649 and 1650 respectively. He was probably the most famous geographer of his time, and his thoughts influenced geography for more than a century. He died in Leyden, in 1650, at the early age of twenty-eight.

The concepts of Varenius on the origin of springs and rivers were a classic case of compromise.[30] He believed it most reasonable to assume that the sea-water hypothesis was correct, but did not exclude the two other factors – precipitation and the conversion of air into water. He advanced two reasons for opting in favour of the sea-water hypothesis. First, rivers bring in a vast amount of water to the sea, and since the sea does not increase in volume, sea-water has to be 'refunded out of the sea into the earth and carried to the heads of rivers'.[31] This can be substantiated by actual observations, namely, the closer a river comes to the sea, the more brackish is its water. Some salt springs are actually supplied with water through direct subterranean conduits from the sea. Second, the sea-water conversion theory alone can explain the presence of water at great depths, as in mines, where it cannot come from rainfall or from the condensation of air. The latter was, in fact, just a restatement of Seneca's theory. However, he still needed to explain how the sea-water reached the heads of rivers and managed to lose its salinity in that process.
This he did by saying:

> 'the bottom of the sea not being in every place rocky, but here and there sandy, gravelly, and oozy, imbibes the sea-water and letteth it into the earth (after the same manner as when we throw water upon sand, beans, peas, wheat, or other grains) thr' whose interstices it is brought by degrees to a great distance from the sea, where at length the small drops come together, especially in straight places, as are mountains, etc. and having found an aqueduct they discharge themselves at a spring.'[31]

The second question was rather difficult to answer as salt could not be removed by percolation or filtration. The rainfall on the ocean was always of freshwater (elsewhere he said that it was sometimes saltish), and hence nature itself had a way of getting rid of salt from the sea-water. If nature can do it in case of precipitation, why can it not be done during the process of percolation? It is also possible that the salt water comes into contact with a vast amount of fresh water, and the subsequent dilution makes it difficult to detect salinity.

Varenius, however, rejected the sea-water hypothesis as the cause of the annual inundation of the Nile, and opted for the precipitation concept.[32]

JOHANN HERBINIUS

The book *Dissertationes de admirandis mundi cataractis supra et subterraneis* by Johann Herbinius was published in Amsterdam, in 1678. Herbinius listed the various probable causes for the origin of rivers and springs as follows: God; continuous movement of water in the subterranean abyss which, by virtue of motion drives the water up to the surface of the earth; angels; stars; the spirit of the earth; and air enclosed within the earth. Strangely enough, Herbinius completely disregarded precipitation as even a possible reason! However, he classified his reasons into two types, true and false; the first two causes were true and all of the others were false. God is the primary cause; the subterranean abyss is the secondary. Figure 9 shows Herbinius' concept of a river originating from a water-filled subterranean cavern.

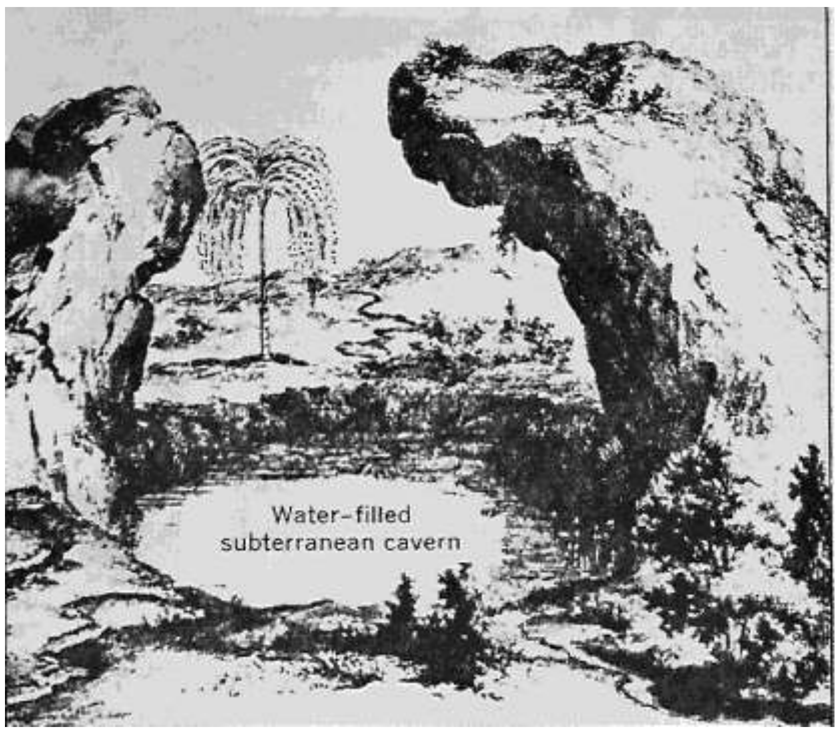

Figure 9. A hydrophylacium within a mountain, filled with water, feeds the nearby spring (after Herbinius).

The Maelström near the island of Mosken, in Norway, particularly attracted his attention.[33] It was:

'no less than 40 miles round, and upon the tides coming in swallowes in a manner the whole sea with an incredible noise, drawing in ships, whales, or whatever else comes within its compass, and dashing them to pieces against the sharp rocks, that there are in the descent of this dreadful Hiatus; and then upon the ebb throwing them out again with a prodigious a violence, in so much that some have attributed the whole flux and reflux of the sea (and not without some reason) to this vast varago.'[34]

The phenomenon (figure 10) served to illustrate his point. The whirlpool indicates an opening in the sea bed, and through it water is sucked in and forced out alternately. The water forced out, he claimed, is responsible for the creation of tides.

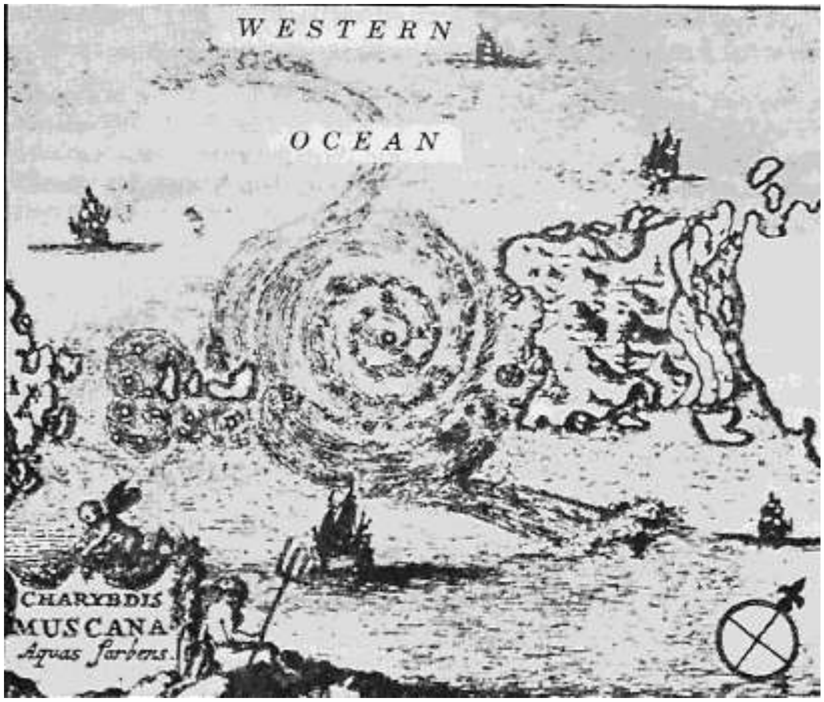

Figure 10. Through a hole in the sea bed in the island of Mosken, Norway, water is sucked in and forced out from the great subterranean reservoir. Water forced out through the hole is responsible for generation of tides (from Herbinius).

BRITISH CONTRIBUTIONS

The major British contributions to hydrology during the seventeenth and the early eighteenth centuries were the evaporation experiments of Edmond Halley, and the rain gauges of Sir Christopher Wren and Robert Hooke. They are discussed in chapters 10 and 11 respectively. With the exception of the above-mentioned scientists, the British contributions to hydrology, in general, tended to be relatively poor in comparison with their achievements in other sciences.

The book *Nature's secrets* by Thomas Willisford, published in 1658, dealt with the subject of hydro-meteorology much in the traditional manner.[35]

John Ray (1627–1705), the English naturalist, achieved most of his fame from his plant classification (which obviously helped the development of systematic botany) but the concept of the hydrologic cycle which he presented also deserves consideration. He believed that sun attracted vapours from the earth and the sea, and that the wind was responsible for driving the vapours from the sea toward the land where it fell as rain. The rivers obtain their supply of water from rain and their interconnection is obvious during the time of flood. A vast quantity of water is carried down to the sea by the rivers annually, and thus, the circulation of water is complete. He did not favour the concept of the subterranean abyss, and commented, 'I hope those who bring up springs and rivers from the great *abyss* will not bring those vapours, which unite into drops and descend in rain from thence tool'.[36]

Ray thought that every natural phenomenon was designed by God for a specific purpose. For example, there is more rainfall on earth than necessary to water it because it brings down a great quantity of earth from the mountains or higher grounds which are then spread on lands during floods – thereby rendering them more fruitful.

Thomas Burnet (1635–1715), an Anglican theologian, had a very vivid and brilliant imagination. His pretentious book *Telluris theoria sacra* (The sacred theory of the earth – containing an account of the original structure of the earth and of all the general changes which it hath already undergone or is to undergo till the consummation of all things), published in 1681, contained a fanciful theory of earth's structure. The book was published under the patronage of King Charles II, and was read in all parts of Europe. In chapter 5, he discussed the water of the primitive earth and the origin of rivers and streams. When the earth was first created, there was no ice, snow, hail, or thunder; and,

> 'as for the winds, they could not be either impetuous or irregular in that earth, seeing there were neither mountains nor any other inequalities to obstruct the course of the vapours; not any unequal seasons, or unequal action of the sun, nor any contrary and struggling motions of the air: nature was then a stranger to all those disorders.'[37]

In the primitive earth, the sun's heat was directed primarily towards the equatorial parts and, consequently, caused most of the evaporation. The vapours raised in this manner were the 'most rarified and agitated; and being once in the open air, their course would be that way, where they found least resistance to their motion; and that would certainly be towards the poles, and the colder regions of the earth.' On reaching colder polar regions, vapours condensed and fell as rain and dew (figure 11). The rain at the poles was continuous due to the vast quantity of water that vapourized in the tropics. Burnet was next confronted with a serious problem: how did water circulate back to the equatorial region as there were no rivers or mountains in his concept of the primitive earth. His answer was rather ingenious. He suggested that the poles had higher elevations than the tropics, and hence, water had to flow downhill and thus form water courses. Hence, the primitive hydrologic cycle consisted of two parts: 'aerial rivers' and surface rivers.

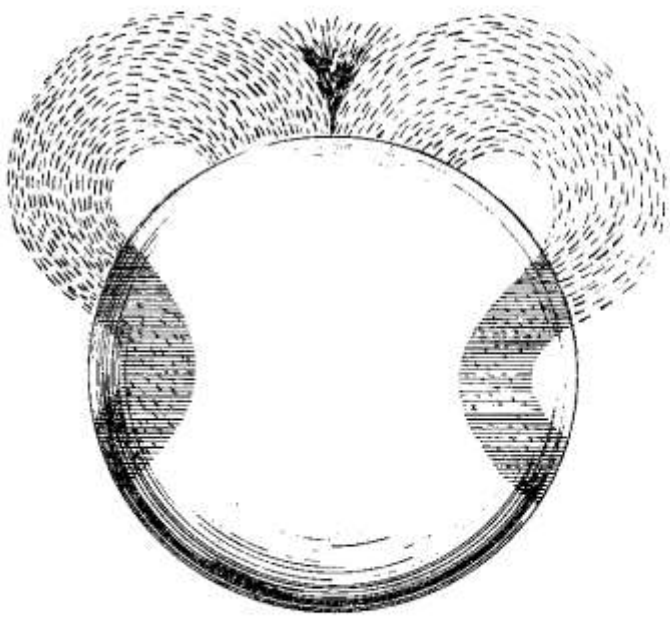

Figure 11. Pattern of evaporation in the primitive earth according to Burnet.

Burnet's work was sharply criticized by Erasmus Warren,[38] the Rector of Worlington, and john Keill.[39, 40] Keill (1671–1721), an 'enthusiastic student of the Newtonian principles', was an able mathematician and astronomer. His objections were precise, and did much to demolish Burnet's fantastic system of air and vapour circulation over the primitive earth. Keill pointed out that an earth without the sea could not possibly supply water vapour to the air. He said:

'And seeing the Sea as it is now laid open to the action of the Sun, is but just sufficient to supply us with Rain and Vapours; does it not seem a thing against common sense to suppose that the Abyss inclos'd with a thick shell could have sent out a quantity of Vapours great enough for such an effect?'[41]

Keill asserted that the sealess earth, instead of being a Garden of Eden as portrayed by Burnet, would be 'nothing else but a Desert'. Keill also disagreed with john Woodward[42] and William Whiston's[43] concept that rivers obtain their source of supply from the subterranean abyss.[44, 45] To him, it seemed almost self-evident that rivers originate from rainfall.

'And as for Rivers, I believe it is evident, that they are furnished by a superior circulation of Vapours drawn from the Sea by the heat of the Sun, which by Calculation are abundantly sufficient for such a supply. For it is certain that nature never provides two distinct ways to produce the same effect, when one will serve. But the increase and decrease of Rivers, according to wet and dry Seasons of the year, do sufficiently show their Origination from a Superior circulation of Rains and Vapours. For if they were furnished by Vapours exhaled from the Abyss through subterraneous Pipes and Channels, I see no reason why this subterraneous fire, which always acts equally, should not always equally produce the same effect in dry weather that it does in wet...

I know the maintainers of this Opinion use to alledge, that there are Springs and Fountains on the tops of Mountains, which cannot easily be maintained by a Superior circulation of Vapours: but I beg those Gentlemens pardon, for I can give no credit to any such Observation; for I am well assured, that there are none of those Springs in some places where it is said they are. And particularly that Learned and diligent Observer of Nature Mr. Edward Lloyd the Keeper of the Musaeum Ashmoleanum assured me, that throughout all his Travels over Wales, he could observe no such thing as a running Spring on the top of a Mountain. On these considerations, I think it is not in the least probable, that Rivers and Springs proceed from Vapour, that is, raised by a subterraneous heat through the Fissures of the Mountains.'[46]

Robert Plot (1640–1696), a Fellow of the Royal Society of London, was interested in the origin of streams.[47] Figure 12 shows his classification of rivers. He was familiar with Perrault's work but he rejected it, and advocated the sea-water theory. He believed that the salt water ascends to mountain tops through tapering passages that finally become capillaries. The movement of water to an elevation higher than that at which it originally stood, was, explained by the pressure of air on the surface of the sea 'just as the quicksilver ascends in the tube of a barometer by the pressure of the air upon the stagnant poole of mercury below'.[48]

In 1695, Dr. John Woodward, Professor of Physic at Gresham College, published a comprehensive book on the natural history of the earth which attracted considerable attention. According to him:

'there is a mighty collection of water enclosed in the bowels of the earth, constituting a huge orb in the interior or central parts of it; upon the surface of which orb of water the terrestrial strata are expanded. That this is the same which Moses calls the Great Deep, or Abyss; the ancient gentile writer, Erabus, and Tartarus.'[42]

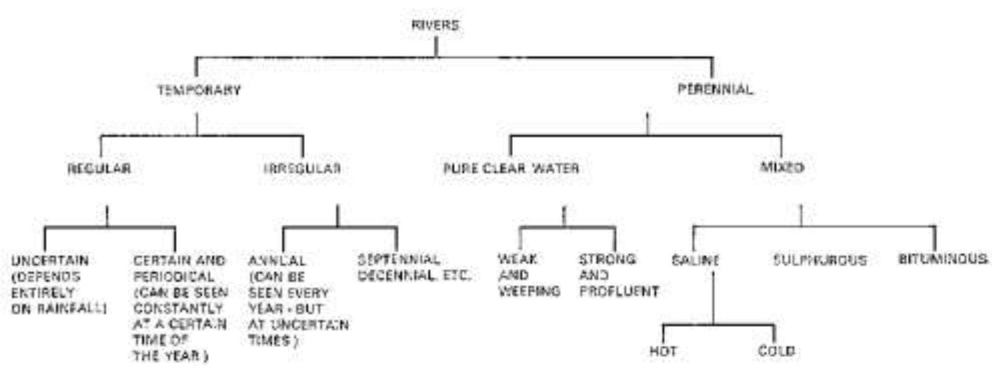

Figure 12. Classification of rivers by Robert Plot.

The abyss communicates with the ocean by means of hiatuses or chasms. All waters of the earth, springs, rivers, vapours, and rains, are supplied from the standing fund of the reservoir of the abyss with its partner the ocean.[49] He did not agree with Halley's conclusions. He suggested that 'springs and rivers do not proceed from vapours raised out of the sea by the sun, borne there by winds unto mountains, and there condensed, as a modern ingenious writer is of opinion'.

Woodward's book did attract several criticisms which were either answered by some of his devoted followers or by the author himself. [50]

ARTESIAN WELLS OF MODENA

Probably the first correct explanation of the nature of artesian wells,[51] was given by the philosopher, astronomer, and geographer al Bīrūni (973–1048) of the Arabian school. The same concept was later mentioned casually by Palissy, and both Giovanni Cassini (1625–1712) and Bernardino Ramazzini (1633–1714) paid considerable attention to the subject. Ramazzini, a professor of the medical school at Modena, wrote a book on the wonderful artesian springs of Modena, in 1691.[52] The book so incensed Robert St. Clair of London that he not only translated the entire work into English but also wrote a lengthy discourse against it.[53] Among his views thereon was the following: 'they come to overturn the Scripture, to establish their own prophane fancies, as our theorist has done, in favour of a spurious brat, of which he will needs be counted the father'.

In his attempt to explain the phenomenon of the artesian wells, Ramazzini said disarmingly that the 'nature of fluid bodies is so abstruse and intricate, that it could never be enough explained by the most solid wits'. The ancient city of Modena has:

'. . . a great abundance of most pure water, which neither can cease through length of time, nor he ever vitiated or diverted by the craft of the enemies: For this city has under its very foundations a great repository of waters, or whatever else it may be called, out of which it draws an inexhaustible stock of waters; and, which is very rare, is got at a very small charge; seeing for the getting of this treasure (for water, according to the testimony of Pindarus, is the best of all things) there is no need of great stir, in digging through mountains, or keeping a great many workmen, as is usual elsewhere, and such as Rome, formerly, had divided, as Frontinus says, into searchers, water-finders, water-bayliffs, conveyors, distributors and many other workmen.'[54]

Water was so plentiful in Modena that any citizen could take as much as he liked from the artesian wells without obtaining permission of the local authorities. The general procedure was to dig to a depth of 63 ft, and then to use an auger to bore a hole for the next 5 ft. A vast quantity of water would thereupon gush out with great force. Subterranean conduits were used to convey water to the public canals which fed a navigable canal. Thus, one could travel by boat all the way to Venice from Modena by way of the canal, and the Scultenna and Po rivers. Ramazzini's explanation of the artesian phenomenon (figure 13) follows:

'First, we may freely affirm, that these waters are not standing, as they are when shut up in a hogshead, but are in continual motion, and that pretty quick, For the noise of that Water which is heard before the perforation in the bottom of the wells does make it manifest enough... And I think 'tis probably the matter is so in our fountains, to wit, the water flows out of some Cistern plac'd in the neighbouring mountains, by subterraneous passages, where the earth is firm and hard; but when it has come into the plain, it expatiates far over the sand, and in the way is lifted up to this height when a hole is made with an auger, according to the Laws of Hydrostaticks.'[55]

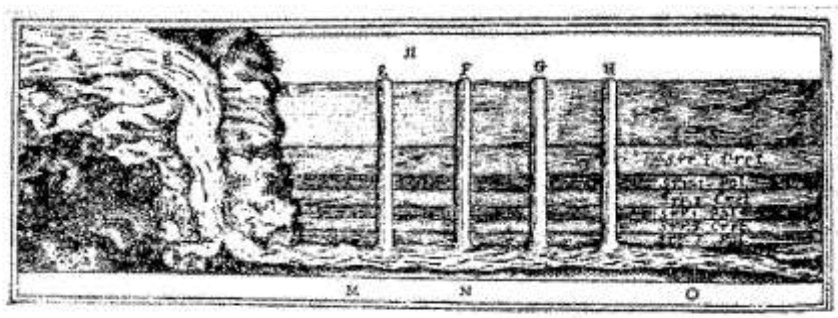

Figure 13. Ramazzini's explanation of the artesian wells of Modena.

'To give some specimen how the flowing of the water may be according to my explication: Suppose, as in figure 10–19 there is a cistern in the bowels of the Appennine, drawing water from the Sea, and that the water is carry'd by subterraneous pipes from the same cistern, the water is forc'd to run down by a more narrow space than it had in the beginning, and to follow its course till it come into the Sea, or some great gulph. Therefore wells E F G H being digg'd without any choice in all the tract lying upon this spring, and the hole being made by the auger, the water of necessity must be lifted up on high, being for'd by another, which descending from a higher ground, presses on that which goes before, and drives it up. By this means these waters receive a plentiful supply from their Father Appennine, as does the well of waters which flows from Lebanon, of which there is mention in the sacred history.

But 'tis, by far, more probable, that the Water is sent from the sea into such Cistern, than from Showers, or melted Snows, seeing Rain and Snow-waters run away for the most part by Rivers above Ground; neither can they enter into the ground so deep; as Seneca also testifies.'[56]

'As I have deduc'd from the Original of this Water from the Sea, so I do not deny, that many Fountains owe their Originals to Rains and melted Snow; yet with this difference, that the Fountains, which have their Spring from the Sea by hidden Passages continue perpetual, but those which rise from Showers and temporary Springs at some time of the year, are diminished and quite dry up... Though I derive the Original of our Fountains from the Sea first, then from some Cistern of Water plac'd in our Mountains, into which the Vapors, sent up by the enclos'd Heat, are returned in Form of Waters. I would not thence infer, that this Cistern is plac'd in the tops of the Appennine Mountains, but I believe rather that 'tis plac'd in the Foot of the Mountain, than in the top... But I cannot certainly conjecture in what part, whether near the foot of the Mountain, or in their inner parts this Cistern of Waters is plac'd by the Divine Architect. I have spar'd no Labour nor Experiences to find out the Head of this Spring, and therefore I diligently viewed not only the Plain towards the Mountains, but the Mountains themselves, and could find no Marks of it.

I observed indeed some small Lakes, but such as dry up in Summer, and so become Pasture for Cattle; of the number of which is Lake Paulinus, 25 miles distant from this. I thought best therefore to fetch the Original of these Waters from another source, viz. from some secret Cistern of Water plac'd in the inner parts of the Appennine Mountains. And it is certain, that the inner parts of the Mountains are cavernous, and that there are in them Cisterns of Water, from whence Fountains and Rivers drawn their Original.'[57]

DOMENICO GUGLIELMINI

The Italian, Giovanni Domenico Guglielmini (figure 14), who contended that Mariotte's contribution to the hydraulic sciences was negligible, tried to solve various problems associated with river flows by field observations. His findings had considerable influence on the developments of concepts of open channel flows, not only in Italy but also throughout the world. Born in Bologna, in 1656, he was a professor of mathematics at the university of his native city. His book *Aquarum fluentium mensura nova methodo inquisita*[58] was published in 1690. In 1692, he became the professor of hydrometry at the university in addition to being the water super-intendent of the district. His major work on the subject[59] was published in 1697, and the following year he was appointed to the chair of mathematics at Padua. Guglielmini, educated in both medicine and mathematics, never really gave up his practice of medicine as a side line. During the last few years of his life he gave up the study of water sciences, and accepted the chair of theoretical medicine. He died in 1710.

Figure 14. Domenico Guglielmini.

Guglielmini, whom Frisi[2l, 22, 60] called a 'great master', was a practical man, and his treatise is primarily on the flow of water in rivers and canals. Toward the late seventeenth century, thanks to Castelli, the continuity equation had become firmly established, but the general principles of open channel flow still needed to be grasped.

It was Guglielmini who supplied some of the basic concepts.[61] He conducted experiments on the efflux principle with greater precision than either Torricelli or Maggiotti, and was convinced that the velocity with which water flowed out of an orifice was proportional to the square root of the head. He extended the same analogy to the cases of flow at a sluice gate and at the inlet of a sloping canal. He believed that:

'... water having a certain depth, the upper parts press the lower with the force of gravity and make them move towards any difference of level, which means in practice that each has that exact grade of velocity which it would have acquired descending from the surface to the place where it is located; we must confess that the velocity of water does not depend only on the descent covered on the inclined canal, but also on the pressure exerted by the upper parts upon the lower according to the rule above mentioned.'[62]

However, he realized that such a condition could not exist in nature, and reasoned that the parabolic distribution of velocity, with zero velocity at the water surface, would be valid only in case of a perfect fluid.[63]

Leliavsky's claim[64, 65] that Guglielmini believed in the parabolic distribution law has to be discounted. It was probably based on Frisi's statement[60] rather than from Guglielmini's work, and the suspicion is further strengthened because of Leliavsky's immediate discussion of the works of Father Grandi (describes in considerable details by Frisi) and Frisi. Elementary concepts of open channel flow can be found from the following excerpt:

'Water passing from rest to motion or leaving the reservoir... acquires in the descent through the rivers, which are on an inclined plane to the horizontal, some degree of velocity, but this very soon reduces to uniformity (equabilità) due to the great resistances that the water encounters in its motion... Once reduced to uniformity, water must, however, maintain the velocity that it acquired previously in flowing on its plane and this is regularly greater, the greater the slope of its bottom.'[66]

The velocity of flow will increase with further increase in flow as the relative effect of resistances will be less, provided it remains, constant. Thus, even though the concept was fundamentally, correct, it was not expressed quantitatively. Guglielmini's sketch, of a free-surface configuration is shown in figure 15.

Guglielmini's reasoning can possibly be extended to obtain the functional relationship between discharge and depth, though the concept was not exactly correct. He said that velocity was proportional to the slope as well as the square root of the depth, which meant that discharge was proportional to depth (3:2), but because of his faulty reasoning he would not receive the credit for the concept. The Italian, however, should be credited for his reasoning that the velocity of flow is dependent on the cross-sectional area, of the channel and inversely proportional to the wetted perimeter.

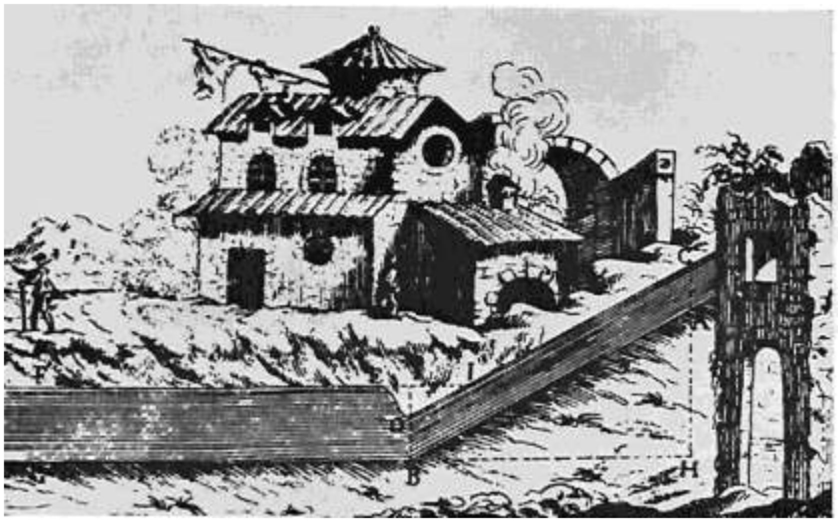

Figure 15. Guglielmini's sketch of free-surface configuration.

NITRE THEORY OF NILE

Toward the latter half of the seventeenth century, a new theory was advanced regarding the annual inundation of the river Nile. It seems to have originated from one Vanslebius who lived in Egypt for some years and who had carefully observed the same phenomenon. The theory was believed by Robert Plot[67] and N. C. De la Chambre,[68] and both of them elaborated on Vanslebius' original concept.

According to the hypothesis, certain kinds of drops, somewhat similar to dews, fell in the valley a few days before the annual rise of the Nile, and fermented the river water. Rainfall was categorically rejected as a reason because, according to the theory's originators, the rains do not usually start till the 25th of June whereas the inundations commence as early as the 12th of that month.

The fermentation causing the rise was said to produce a kind of green scum on the water surface. Plot agreed with Cambracus and Gassendi that the fermentation was caused by the presence of nitre.[67] Plot asserted, on the authority of Vanslebius, that the inundation of the Nile was not an isolated phenomenon as water levels in wells in certain parts of Egypt have been observed to

> 'rise the very same night, and in the same manner with the river, which having no possible communication with the rains in Habessia, shows evidently that the increase of the water in the river, comes partly at least from another cause, and most likely from the fermentation made by the nitre, which however it comes to pass seems to leave its own parts (whereof there are abundance in Egypt) at the time of the increase and goes into the river.'[67]

N. C. De la Chambre[68] believed that the drops also made the mud of the Nile heavier than before, and the total rise of the river in any year could be predicted by the relative weight of the mud. The special mud did not create any problem of sedimentation because the nitre was volatile and, consequently, the heights of the banks had remained constant for more than 2000 years (from the time of the Greek historian, Herodotus). Figure 16 is a topographical map of the source of the Nile according to De la Chambre, on which the locations of nitre pits are shown.

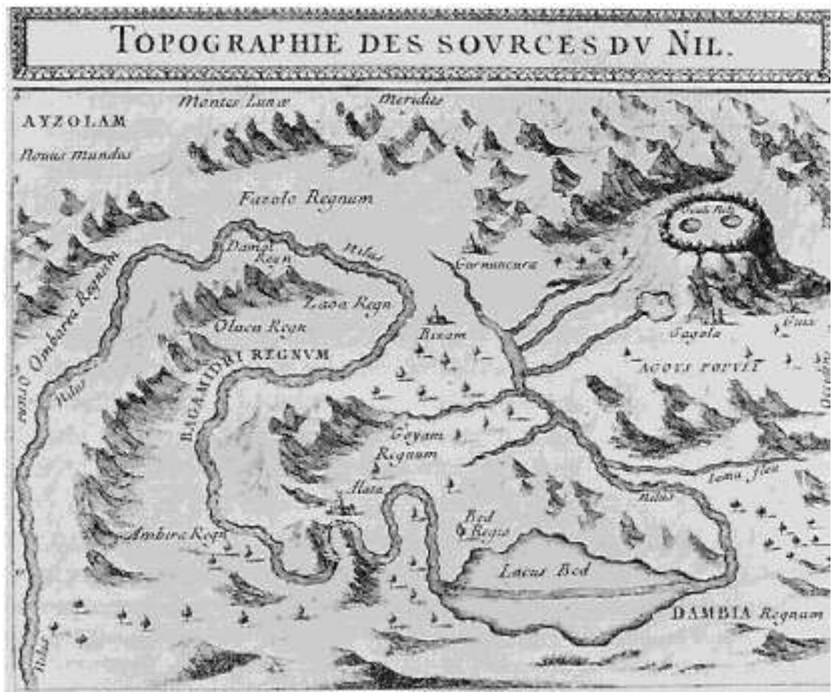

Figure 16. A map of the source of the Nile indicating the presence of nitre pits (after N. C. De la Chambre).

ORIGIN OF STREAMS

The cause or causes of the origin of springs was an extremely popular subject in the seventeenth century, and practically every man of importance expressed his opinion on it. Some of the opinions have already been discussed, and other significant ones will now be mentioned briefly.

Molina (1536–1609) correctly suggested that rivers originated from rainfall which penetrated the earth's crust, but the idea was opposed by Riccioli who held that precipitation could not percolate to more than 12 to 15 feet and much less so in the rocky countries of Peru and Chile where streams are abundant.[69] He quoted from *Genesis*: 'The Lord had not yet rained upon earth', but 'A fountain ascended from the earth which watered its entire surface'.[*] The subterranean condensation theory was disregarded as it was considered to be too slow a process. According to his calculations, the Volga alone carried enough water to the Caspian Sea every year to inundate the entire earth – a conclusion that was later quoted by Plot in support of his own theory. Riccioli stated that all good Catholics should accept the explanation in Ecclesiastes.[70]

Dobrzensky[71] opposed the pluvial theory on the same grounds as Riccioli, and he suggested two other causes. The remote cause was the tides of the sea, and the local one was the subterranean condensation of air.

Isaac Voss categorically denied the sea-water conversion theory. He believed that all rivers originated from rainfall, but his credibility is somewhat marred by the ridiculous ideas he expressed on other subjects. Among others who expressed correct opinions were Fabri,[72] Bartholinus[73], and Robert Hooke.[74]

In the treatise on 'Running waters', Carlo Fontana,[75] an Italian, stated that the sea must be higher than the highest mountains as no landmarks are visible if one, at sea, is a few miles off shore. He obviously failed to consider the curvature of the earth! The hypothesis, however, provided an excellent base for explaining the movement of water from the sea to the mountain tops: after all, water was not rising above its own level!

ADVENT OF CURRENT METERS

Most works in the field of hydrometry credit Henry Pitot and Reinhard Woltman with the earliest development of sophisticated velocity-measurement devices during the eighteenth century. The earliest current meter, however, was probably constructed[76] by an Italian physician, Dr. Santorio Santorio (1561–1630), around 1610. Santorio became interested in the subject in a curious way; he wanted to evaluate the critical velocities under which his patients were lulled to sleep by the soft noise of quietly falling water as contrasted with the loud noises produced by rapidly falling waters which would keep them awake. Hence, he proposed:

> '... as a means of subtly ascertaining the reason for those circumstances, that one should weigh, with a balance scale, the amount of impact produced under both [circumstances]. When urged by friends to show how that could be done, I prepared two staters [Roman balances] on both of which a plate is fixed at right angles. By means of the first [with the plate pointing upwards], the impact of winds could be weighed; by means of the second [with the plate pointing downwards], the impact of the water. The one having the plate pointing upwards for measuring the impetus of the winds helped us to predict when such winds tended to increase. We could thus foresee heavy weather at sea, and could avoid the perilous sinking of ships. It at least provided a means whereby we could be more sure

[*] Genesis II, 5–6, 'Nondum pluerat Dominus super terram... Fons ascendebat terra irrigans universam superficiem terrae'.

whether the impact of winds tended to increase or decrease. Other uses for this device are describes in the book regarding medical instruments. The other instrument, on which the same [size] plate hangs downward, allows us to weigh the amount of impact produced by running waters. It might have primary usefulness for improving the efficiency of [water] mills, and for many other applications. In consequence of its use, we shall be able to ascertain what amount of impact has beneficial [medical] properties, and what amounts would have harmful properties. Actually, if certain measures of impetus or noise are salubrious, and others are unsalubrious, by what better method could we graduate the strengths of the medicines we are to take in.'[77]

Santorio's drawings of the two instruments are shown in figures 17 and 18.

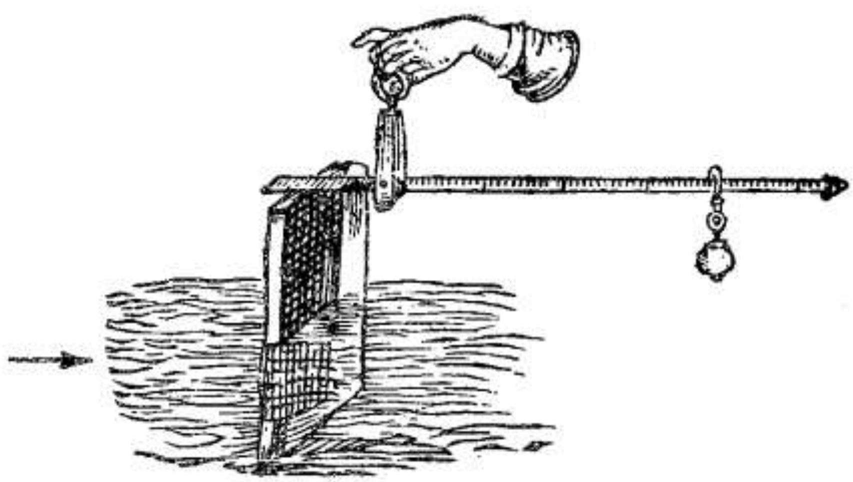

Figure 17. Santorio's water current meter.

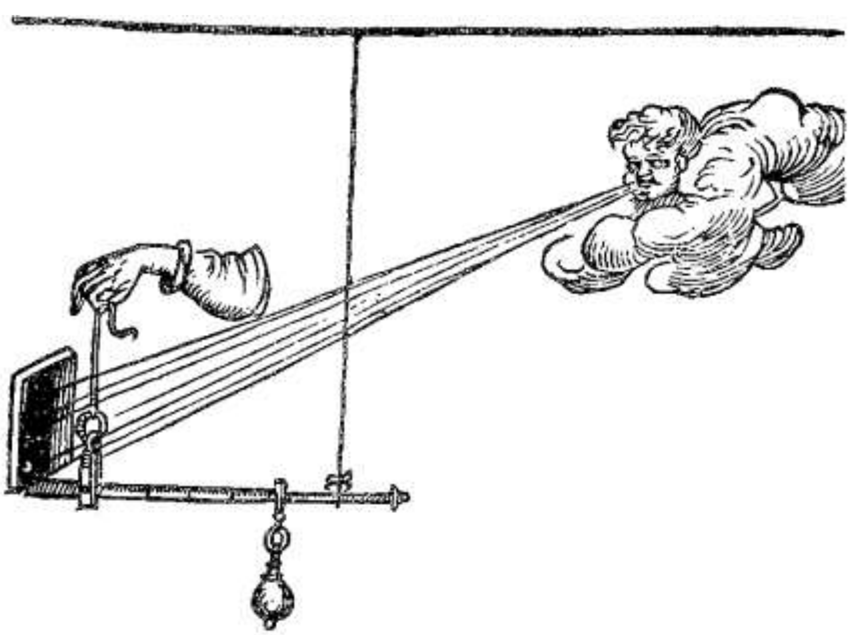

Figure 18. Santorio's anemometer.

The instrument only measured the impact of water striking the plate, and no effort was made to convert the data into water velocities. In fact, the mathematical tools for making such conversions had not yet been conceived.

Robert Hooke, the inventive genius, also designed an early current meter. An entry in the volume VI of the *Register book* of the Royal society of London entitled 'A way-wiser* for sea' and dated November 98, 1683, reads:

> 'I shewed an Instrument I had contrived and shewed some of the Society about go years since, By which the way of a Ship through the Sea might be exactly measured as also the Velocity of any running Water or River and thereby the comparative velocity of it in its several parts, by this also the quantity of the water vented by any River into the Sea or any other River might be found.'[78]

Unfortunately, no sketch of Hooke's current meter seems to have been preserves. Frazier, however, has reconstructed[79] its rotor from other descriptions (figure 19). He comments that:

> 'the facilities Woltman provided for counting the revolutions are identical with those which Hooke had provided; and if Hooke's rotor had been made in an appropriate size, and were mounted on a frame such as that which Woltman had adopted, it could probably have served the purpose even better than Woltman's.[79]

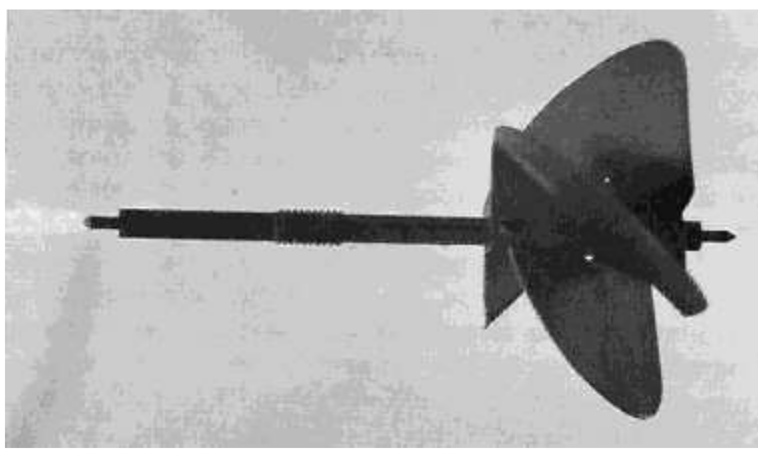

Figure 19. Model of the rotor for a sounding apparatus of Robert Hooke (reconstructed by Arthur H. Frazier).

CONCLUSION

Looking back, the greatest achievements of the seventeenth century, omitting the contributions of Perrault, Mariotte and Halley, were the restatement as well as the general

*A ship's long in this case.

acceptance of the continuity principle. The credit for it must go to Benedetto Castelli, even if he obtained the idea from Leonardo (which is debatable). One has to applaud him for his contribution to make the principle widely known and, what is more important almost universally accepted. The resurgence of interest in practical hydrologic engineering was obviously due to the importance of irrigation, river-training, and flood control projects. The construction of such works gave rise to innumerable problems that could only have been successfully solved by a better insight to the physical phenomena involved. Probably if the responsible engineers of that day encountered a particular problem, they would first turn to the Greek and the Roman masters for an answer, but in most instances they would have been disappointed. Thus, they had to find their own solutions and this circumstance alone was a significant step forward. The hydrologic field was dominated by Italians in the seventeenth century, notably by Castelli, Torricelli, Ramazzini, and Guglielmini. This circumstance extended well into the eighteenth century with the works of engineers like Vallisnieri, Manfredi, Grandi, Frisi, and Poleni. The explanations of Ramazzini regarding the artesian wells of Modena and the observations of Guglielmini on the open channel flow also deserve special mention.

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