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The sixteenth century

INTRODUCTION

During the later Middle Ages in general, only the people who desired to join the learned professions of Church, law, and medicine were educated at the universities,[1] and the entire intellectual attainment of Europe rested primarily on the scholars. An average man was contented if he was considered to be a good Christian (meaning that he was capable of reading the Bible and that he worried about saving his soul). The medieval scholar believed that many religious truths, like miracles, should remain unreasonable and inexplicable. When he asked himself questions such as ‘from whence comes the water of a spring?’ he first referred to the Scriptures. If he did not find it there, he might have looked into the works of the Greek or the Roman philosophers or even into those of his Islamic predecessors for the answers. But he did not, in general, venture to propose explanations of his own for such natural phenomena and, consequently, it is not surprising that the sciences of hydrology and meteorology did not advance much during those ages.

The first indications of a divorce between science and philosophy can be traced to about the beginning of the twelfth century, although a final split did not come until a few centuries later. The word philosophy included any type of inquiry, scientific or philosophical, using the roots of the modern terms. The Church had dominated the secular knowledge for such a long time that the impetus of individual independent thoughts like those of Roger Bacon or Leonardo were unable to produce any significant effect on the status of science. It is true that the refreshing breeze of both the renaissance and the reformation brought an acceptance of new ideas again, but the writings of the old Greek masters kept on being dissected and summarized with monotonous regularity. It was just the same old wine with only a new label on the bottle. With very few exceptions, people preferred book learning to observations of nature, and universities concentrated on classical literature. So far as experimental science was concerned, universities were as intolerant of it as was the contemporary Catholic Church. Such were the unfavourable conditions concerning the advancement of knowledge when the great Italian genius, Leonardo da Vinci, was born.

LEONARDO DA VINCI

Leonardo da Vinci (figure 1), illegitimate son of a Florentine lawyer, was born in 1452 in the small Tuscan village of Vinci, in Italy. In 1481, he wrote an extraordinary letter offering his services to Ludovico Sforza, the Duke of Milan, a copy of which is still in existence, though not in his own handwriting. In the letter he proclaimed himself to be an expert military engineer, architect, civil engineer, and mentioned that as a sculptor or painter ‘I can do as well as anybody else, no matter who he may be’. The letter achieved its objective and it would probably be true to say that he far surpassed his every claim. He died at Amboise, in France, in 1519.

Figure 1. Leonardo da Vinci (by courtesy of Uffizi Gallery, Florence).

Leonardo was a genius, and few people, if any, will disagree with that statement. According to Benvenuto Cellini, Francis I believed that no other man 'had attained so great a knowledge as Leonardo, not only as a sculptor, painter and architect, but beyond that, as a profound philosopher'. Some have claimed that Leonardo even anticipated the discoveries of Francis Bacon, James Watt, Isaac Newton, and William Harvey, but that could be stretching the cult of the Florentine too far. At the other extreme, it has been said that Leonardo's techniques show very little originality, and that his works largely reflect those of Francesco di Giorgio (1439–1500) and other engincers.[3] Obviously, the truth lies somewhere between those two extremes. Be that as it may, he gave hydrology and hydraulics a great boost along the road to progress, but the fact that it did not take place, was partly due, to his own faults.

Leonardo was a prolific writer. He started accumulating his notes at the age of about 37, and continued doing so almost until the time of his death. Despite the facts that he had filled over 7000 sheets with valuable notes and sketches on scientific subjects, and that publication facilities were then available, he did not publish any of them. He used severe condensations, and his notes were, written in 'mirror image' handwriting, a method that seems to be natural for a select few left-handed persons. Leonardo, however, was aware of his shortcomings, and in one of these manuscripts, which is at present at the British Museum, he wrote:

> 'This a collection without order, drawn from many papers that 1 have here copied, hoping later to put them in their right order, according to the subjects which they treat. I fear that I must repeat myself frequently; do not blame me for this, reader, because the subjects are numerous and the memory is unable to have them all present and say: 'I shall not write this because I wrote it before.'[4]

At the time of his death, the entire collection of notes was bequeathed to his young friend and companion, Francesco Melzi, who screened them for whatever they may have contained about Art, and largely ignored the others. Those 'discards' were eventually tied into between one and two dozen bundles, and were either given or sold to an equal number of libraries or individuals. And even after that took place, they continued to receive very little public attention. Eventually, some of them came to the attention of an outstanding hydraulic engineer, Giovanni Batista Venturi (1746–1822), the man for whom Clemens Herschel named the modern Venturi meter. After he had examined the notes, Venturi wrote an article entitled *Essai sur los ouvrages physico-mathématiques de Leonardo da Vinci* which was published in 1797. It revealed what a truly modern scientist Leonardo was as of that date, but more importantly, it stimulated the production of a still-continuing deluge of books and articles about him. Of particular interest here is the fact that by far the largest number of Leonardo's notes were devoted to hydrology and hydraulics than to any other single subject.

Leonardo on the hydrologic cycle

Leonardo's concepts on the hydrologic cycle have never received a thorough examination, and this is not surprising as only two serious studies have been made so far thereon. Both

Adams[5, 6] and Meinzer[7], [8], who conducted them, concluded erroneously that Leonardo had a correct understanding of the concept of the hydrologic cycle. In his book on *The birth and development of geological sciences*, Adams reported:

'Leonardo da Vinci ... was one of the earliest to see the true explanation of the origin of rivers. He wrote but little on the subject, yet from his observations in the Alps he recognized the important role played by the more pervious beds in the synclinal folds of great mountain ranges, especially when they are dipping at a high angle and lie between impervious beds, in carrying the rain and snow waters deep down into the crust of the earth, whence they may be brought again to the surface at some distant point or perhaps onward into the ocean without again reaching the surface at all.'[9]

Adam's statement was based on a secondary source of Leonardo's work by De Lorenzo.[10] Later, Meinzer quoted a passage from the Richter-translation of Leonardo's notes to support his contention that the Italian had a correct concept of the hydrologic cycle.[8] Unfortunately, the lines quoted, if studied in their proper context, reveal Leonardo's error. The statements of Adams and Meinzer have been widely quoted by subsequent writers. Not all of them shared those opinions, however. For example, Krynine, who has been mentioned previously in this work, never did credit Leonardo with having expressed the correct concept.[11] Be that as it may, a fairly thorough search of Leonardo's actual notes indicates that during the course of a long period of years, Leonardo did make a few clear and currently acceptable statements regarding the nature of the hydrologic cycle. A brief explanation of the circumstances follows.

From his familiarity with the writings of Pliny (23–79 A.D.) and Galen (130–200 A.D.), the founder of experimental physiology, it may be assumed that they might have had an appreciable amount of influence on Leonardo's thoughts, especially on the hydrologic cycle, as will soon become evident. Pliny, in his *Natural history* (II, 24, 66), stated:

'Water penetrates the earth everywhere, inside, outside, above, along connecting veins running in all directions, and breaks through to the highest mountain summits - there it gushes as in siphons, driven by pneuma (spiritus) and forced out by the weight of the earth; it would seem that the water is never in danger of falling; on the contrary, it bursts through to high places and summits. Hence, it is clear why the seas never grow from the daily influx of river water.'

Galen's influence was of a different nature. In following his example, Leonardo dissected numerous cadavers and searched for similarities. not only between structural make-up of man as compared with other living creatures on the earth, but also between man and inanimate objects such as the world itself. This is shown in the following thoughts he had prepared for use in his planned (but never completed) *Treatise on water*:

'By the ancients man has been called the world in miniature; and certainly this name is well bestowed, because, inasmuch as man is composed of earth, water, air, and fire, his body resembles that of the earth; and as man has in him bones, the supports and framework of his flesh, the world has its rocks, the supports of the earth; as man has in him a pool of blood in which the lungs rise and fall in breathing, so the body of earth has its ocean tide which likewise rises and falls every six hours, as if the world breathed; as in that pool of blood veins have their origin, which ramify all over the human body, so likewise the ocean sea fills the body of the earth with infinite springs of water. The body of the earth lacks sinews, and this is because the sinews are made expressly for movements and the world being perpetually stable, no movement takes place, and, no movement taking place, muscles are not necessary. But in all other points they are much alike ... if the body of the earth were not like that of man, it would be impossible that the waters of the sea – being so much lower than the mountains – could by their nature rise up to the summits of these mountains. Hence it is to be believed that the same cause which keeps the blood at the top of the head in man keeps the water at the summits of the mountains.'[12]

He carried the thought a step further:

'The same cause which moves the humours in every species of animate bodies against the natural law of gravity also propels the water through the veins of the earth wherein it is enclosed and distributes it through small passages. And as the blood rises from below and pours out through the broken veins of the forehead, as the water rises from the lowest part of the vine to the branches that are cut, so from the lowest depth of the sea the water rises to the summits of mountains, where, finding the veins broken, it pours out and returns to the bottom of the sea. Thus the movement of the water inside and outside varies in turn, now it is compelled to rise, then it descends in natural freedom. Thus joined together it goes round and round in continuous rotation, hither and thither from above and from below, it never rests in quiet, not from its course, but from its nature.'[13]

While the foregoing translations from Leonardo's own statements may seem to have little resemblance to the modern concept of the hydrologic cycle, it is important to consider that on the very same sheet which contained the longer thereof, Leonardo made the following statement:

'Where there is life there is heat, and where vital heat is, there is movement of vapour. This is proved inasmuch as we see that the element of fire by its heat always draws to itself damp vapours and thick mists as opaque clouds, which it raises from seas as well as lakes and rivers and damp valleys; and these being drawn by degrees as far as the cold region, the first portion stops, because heat and moisture cannot exist with cold and dryness; and where the first portion stops the rest settle, and thus one portion alter another being added, thick and dark clouds are formed. They are often wafted about and borne by the winds from one region to another, where by their density they become so heavy that they fall in thick rain; and if the heat of the sun is added to the power of the element of fire, the clouds are drawn up higher still and find a greater degree of cold, in which they form ice and fall in storms of hail. Now the same heat which holds up so great a weight of water as is seen to rain from the clouds, draws them from below upwards, from the foot of the mountains, and leads and holds them within the summits of the mountains, and these, finding some fissure, issue continuously and cause rivers.'[14]

Here then, on the same page of notes, are two seemingly divergent concepts concerning the hydrologic cycle – one correct, the other in error, as viewed on the basis of our present ideas on the subject. Characteristically, Leonardo reported an occasional doubt about certain aspects of both theories, but nothing has been found so far which would indicate that he had at any time discarded the basic concepts of either of them. In fact, the chances seem good that he believed both systems operated concurrently. One can easily imagine Leonardo observing a mountain stream (which he considered a ruptured vein) in the side of the mountain during a sudden shower, with the water falling from the clouds supplementing the flow of the spring. The final paragraph in the above quotations seems to contain evidence that he was trying to express that very thought.

In view of what has been said here, it is admitted that not all of Leonardo's conception of the hydrologic cycle was in agreement with that which is currently held, but it is nevertheless contended that he should not, for that reason be denied the right to receive full credit for having clearly and correctly expressed the basic feature of the modern concept thereof.[16] Figure 2 is a diagrammatic representation of such a concept.

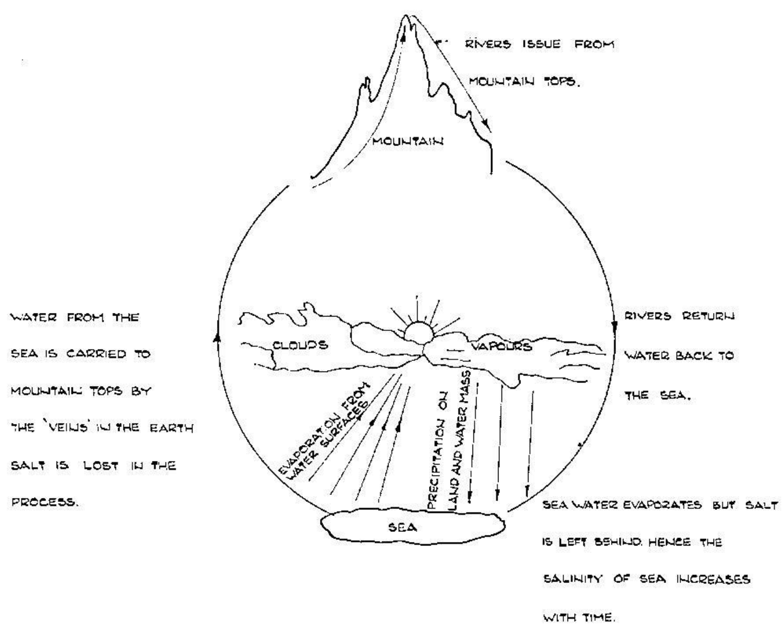

Figure 2. Leonardo's concept of the hydrologic cycle.

Leonardo on open channel flow

Leonardo had a better understanding of the principles of flow in open channels than any of his predecessors or contemporaries, and it is not surprising as his ideas were based on observations. He was interested, ever since his youth, in the study of the various physical characteristics of mountains, rivers and seas. Figure 3, for example, is a photograph of two conjugate pages from Leonardo's works, one of which shows a philosopher* contemplating, and the other is several studies of whirling water. Except for a few isolated instances, the observations were made on the spot, and by himself. His characteristic attitude was that to draw valid conclusions, one must rely on experience and experiments. Fortunately for hydrologists and hydraulicians, various scholars have re-arranged the writings of Leonardo on water from his many manuscripts, notably Arconati[17] (1643), Cardinali[18] (1826), MacCurdy[15] (1928) and Richter[13] (1939), the last two being English translations.

Figure 3. Two conjugate pages from Leonardo's notebooks. One shows a philosopher (Leonardo?) contemplating, and the other shows a series of sketches of whirling water.

Leonardo has discussed flow in open channels many times, and had obviously a clear concept of the principle of continuity, so much so that it can be named after him with complete justification. Consider the following passage:

'Given two rivers of equal volume of water at their entrances their exits will an equal; that is, given an equal volume of water in an equal time, even though rivers may vary in length, breadth, slant and depth and the one be twisted and the other straight; or though both be twisted but the shapes of their curves are unlike, or one he of uniform breadth and the other of varying breadth; and if both vary their variation may be different; one may be of uniform depth and the other of varying depth; and should both depths vary in themselves their variation may not have any kind of likeness; and the whole of one may be uniformly swift and the other uniformly slow, or the slowness and swiftness of one may be mixed ...; and the fact that there exist in these two rivers infinite varieties of currents in

*The philosopher depicted could have been a self-portrait of Leonardo, but it is not certain because Leonardo was not so old at the time of the drawing.

breadth, length, slant and depth will not therefore prevent the equal entrances of the one and the other from being equal in their exits.'[19]

He offered the now familiar analogy of the principle:

'Let us imagine an avenue formed of three consecutive sections, each of a different width; the first section, the narrowest [figure 4] is 4 times less wide than the second, and this one [the second] is twice narrower than the third; people, closely pressed against each other, fill these avenues; they must march together in a continuous manner; when the people in the large avenue take one step forward, those in the middle one must make two and those in the smallest, eight; a proportion which you will find in all motions passing through sections of width.'[20]

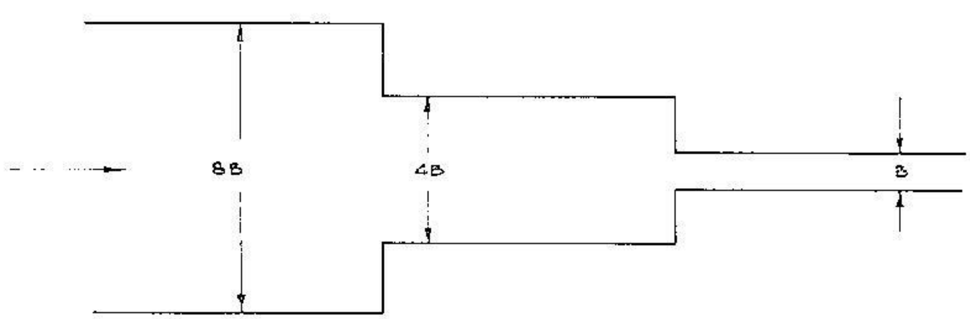

Figure 4. Continuity analogy of Leonardo

Leonardo was aware of the major part played by slope in open channel hydraulics:

'where the channel of the river is more sloping the water has a swifter current; and where the water is swifter it wears the bed of its river more away and deepens it more and causes the same quantity of water to occupy less space.'[21]

Velocity of flow

Consider the following statements of Leonardo:

'Waters which fall from the same level with an equal slant in an equal length of movement will be of equal swiftness.'

'Of waters which fall from the same level by channels of equal slant, that will have the swifter course which has the greater length.'

'Of waters which fall the same distance from the same level, that will have the swifter course which has the greater length.'

'Of waters which fall the same distance from the same level, that will he slower which is longer.'

The concept was obviously erroneous because there is a direct functional relationship between velocity and distance. Had he introduced a time element instead of the distance, then undoubtedly, he would have postulated one of the fundamental laws of motion (velocity = acceleration X time) nearly a hundred years before, Galileo. However, he did realize that the accelerated motion cannot, continue indefinitely because of side and bottom resistances, and he also had an excellent concept of velocity distribution.

‘Water has higher speed on the surface than at the bottom. This happens because water on the surface borders on air which is of little resistance, because lighter than water, and water at the bottom is touching the earth which is of higher resistance, because heavier than water and not moving. From this follows that the part which is more distant from the bottom has less resistance than that below.’[22]

Figure 5 is an artist’s conception of how Leonardo conducted his studies on velocity distribution in rivers. The rod floats near his helper are from Manuscript ‘A’, folio 42 verso, Institut de France. His sketch of the float is as shown in his note-book. Leonardo is keeping abreast of the float in the mid-river as it moves downstream. While doing so, he measures the distance travelled by means of his odometer; and he measures the time in which it travels that distance by singing musical scales up and down eight to ten times.[23] The other floats, held together by a piece of string instead of a wooden rod, and lying behind his helper, are from Codice Leicester, folio 13 verso. The surveying level and pitcher (for filling the groove cut into the top surface of the level) are from Codice ‘B’, 2173, folio 65 verso, Institut de France. Leonardo used a level, probably like the one shown, to determine the slope of the river. This is probably the first serious attempt to determine the velocity of flowing water by means of floats.

Figure 5. Measurement of velocity by Leonardo (reconstructed by Arthur H. Frazier).

Treatise on water

Leonardo planned to write a treatise on water and even went to the extent of dividing it into fifteen books. The classification was as follows:

Book 1 of water in itself,
Book 2 of the sea,
Book 3 of subterranean rivers,
Book 4 of rivers,
Book 5 of the nature of the depths,
Book 6 of the obstacles,
Book 7 of different kinds of gravel,
Book 8 of the surface water,
Book 9 of the things that move in it,
Book 10 of the repairing (the hanks) of rivers,
Book 11 of conduits,
Book 12 of canals,
Book 13 of machines turned by water,
Book 14 of raising water,
Book 15 of matters worn by water.

Even though his intention was evident, he never did complete the work. His manuscripts, especially Codex Leicester, contain a vast array of notes, figures, as well as brief outlines for chapters for the proposed work. One such note, dealing with precipitation, for example, reads:

> 'Write how clouds are formed and how they dissolve, and what it is that causes vapour to rise from the water of the earth into the air, and the cause of mists and of the air becoming thickened, and why it appears more blue or less blue at one time than another. Write in the same way of the regions of the air and the cause of snow and hail, and how water contracts and becomes hard in the form of ice, and of the new shapes that the snow forms in the air …'[24]

If Leonardo had completed the book and had he arranged to publish it, the history of hydrology and hydraulics (or call it water resources engineering) would have undoubtedly acquired an entirely new dimension during the period of his own lifetime.

Other hydrological concepts of Leonardo

The Roman water commissioner Frontinus, some fourteen centuries before the time of Leonardo, had a vague notion that discharge through an orifice was dependent on the head of water. Leonardo's statement about it was more precise than that of Frontinus, but he too, erred somewhat. Leonardo proposed that a simple direct functional relationship existed between the head and the velocity of the discharge. He then extended this same analogy to other hydraulic problems, notably to the cases of weirs and sluice gates. He even gave an example, namely: if the head of water over a weir is increased from 2 to3 inches, then the lower-most inch doubles its power, velocity, and discharge.[17]

Leonardo was one of the first men to study river bed configuration systematically. He was quick to realize that the velocity of water is higher at the centre of a regular channel than at the sides because of the frictional effect of the banks. He must have taken a great interest in the flow of water in rivers and channels. It is quite certain that he used models for such studies. His notebooks contain sketches of small channels in wood which were used for his experiments. He used dyes to study the motions of water, and his comments and drawings even indicate his use of glass sides on some of his flumes to facilitate better observations. One of his model studies, for example, was concerned with the nature of sedimentation behind an obstacle on a river bed. He placed sand at the bottom of a wooden channel, and placed a stone at its centre to represent the obstruction. Sandy water was used in this investigation, and it was observed that rather heavy sedimentation occurred behind the obstacle. Admittedly, the results of most of Leonardo's model studies were qualitative rather than quantitative, as in the above example, but one must nevertheless admire him for his efforts.

Leonardo believed that the salinity of the sea was caused by various rivers which passed through salt deposits and subsequently discharged their high salt content into the ocean, and that the salinity gradually increased with the evaporation of water from the sea.
He observed that sea-water contains 'more salt in our time than it has ever been at any time previously'.

The irrigation, drainage, and flood control theories of Leonardo have been discussed in considerable detail by Parsons.[25]

GERONIMO CARDANO

Geronimo Cardano (1501–1576) was a voluminous and repetitious writer. Because his works were read fairly extensively, he was quite influential during the latter half of the sixteenth century. It is said that he plagiarized freely from the manuscripts of Leonardo (which means that the Italian had at least some influence on science through such plagiarists). Cardano reduced the traditional four elements to three[26] by omitting fire. He also reduced the four qualities to two, by omitting heat from the sky and moisture from the three elements.

He believed that the earth, like a sponge, was full of subterranean water,[27] and that the proportion of land greatly exceeded that of water. Water remains on the surface of the earth only because there is not enough room for it inside. This concept, he believed, is consistent with the observed fact that water always tends to flow downwards.

Cardano thought that streams start from little drains or gullies which collect condensed vapour from both above and below the ground. When rain and melted snow increase their volumes, they become rivers. He was confident that the chief source of supply of water for the rivers came from the conversion of vapour into water. Although Cardano plagiarized principally from Leonardo, he seems to have preferred Aristotle's writings on the origin of springs. The terms air and vapour were synonymous during the sixteenth century. In fact almost a century later, when discussing Cardano's concept, the eminent German geographer Bernhardus Varenius stated that there is but little difference between air and vapours'. Cardano had justified his conclusions with the observation that if anyone observed mountains in the early mornings, he would see a superabundance of moisture surrounding them. River stages accordingly rise in the morning, especially if they are near mountains, because of the water generated within the mountains by the coolness of the rocks and outside of them by the coolness of the nights. Later Pierre Perrault criticized[28] this opinion.

BERNARD PALISSY – THE POTTER

Bernard Palissy (figure 6) is attributed to have been born in 1499, 1510, or some time between 1514 to 1520, the most probable date being 1510.[29] He began his career making stained glass windows, but he had to do land surveying to supplement his income in order to support his wife and six children. After sixteen years of tireless experimentation, Palissy perfected a technique for making enamelled pottery which brought him fame and fortune. Later, he even applied his new art to decorating castles!

Palissy was one of the first to embrace the new Protestant religion in Saintes during Reformation and, had it not been for one of his chief patrons, Arne de Montmorency (high constable of France and the governor of Saintes) taking the case for which he was being tried, directly to the Queen Mother Catherine de Medicis, he would almost certainly have been executed. During the Civil War of 1588, he was imprisoned, and died in Bastille de Bussy in 1590, an old and broken man.

Palissy loved nature, and his theories were, in general, based upon personal observations thereon. Thus, his views were often in conflict with those of the established authorities – a circumstance which did not worry him much – in fact, it added to his zeal for carrying on his own scientific investigations. His book *Discours admirables*, published in 1580, was written in French although the prevailing language of the scholars was Latin – a fact that probably explains why it never received as wide an acceptance as it deserved. Palissy himself claimed that he had no knowledge of either Latin or Greek, but Thompson[30] has suggested that his claim may have been only a pose. Duhem has claimed that the potter was a shameless plagiarist.[31]

Figure 6. Bernard Palissy (by courtesy of Librairie Honoré Champion, Paris).

Nevertheless, Palissy had a correct attitude toward experimental sciences such as paleontology, hydrology, geology, botany, agriculture, chemistry, zoology, and minerology – just to name a few of those in which he was interested. In his discourses he made use of two fictitious persons: Theory, the one who inquires, and Practice, the one who replies. Practice was the name under which he commonly distinguished his views from those of the establishment.[32]

According to his sympathetic biographer Morley:

‘Theory might well ask, looking back upon the whole body of doctrine taught by the old Potter in the last years of his life,
Where have you found all this written? or tell me in what school you have been, from which you might have learned what you are telling me.
Practice – I have no other book than the heavens and the earth, which are known of all men, and given to all men to be known and read. Having read in the same 1 have reflected on terrestrial matters, because I had not studied in astrology to contemplate the stars.’[33]

The hydrologic cycle

It has already been shown that up to the time of Palissy very few persons had a correct understanding of the hydrologic cycle, but none of them had ever stated it as forcefully as the Huguenot.[34] Because Palissy was familiar with Vitruvius’ work, it is possible that he obtained his idea initially from the Roman, but even so, one has to admire his substantiation of the theory with actual observations of nature, carried out with sound logic by himself.

Palissy in the guise of Practice, stated categorically that rivers and springs cannot have any other source than rainfall, whereupon he was called a 'great dolt' by Theory for being presumptuous enough to attempt to contradict the most excellent philosophers of all times. This did not worry him, for he had confidence that his theory was correct. With great skill and logic, he refuted the age-old theories that streams originated directly from sea- water or from air that had been converted into water. He used the concept of gravity effectively against the first theory by claiming that if the theory were correct, the level of the sea would have to be higher than that of mountains at the tops of which the rivers were supposed to originate, that their waters would have to be saline, and that they would have to dry up during periods of low tide. It is true, the potter argued, that rivers do tend to dry up sometimes but the period does not coincide with low tides; in fact, the phenomenon occurs even in summer when rainfall is lacking – a fact which tends to support his own opinion. The maximum tidal levels are associated with the full moons of March and July and, hence, if the theory of his opponents was true, infinite numbers of wells and rivers could not go dry during the months of July, August, and September. Even assuming that the sea level was as high as the mountains, the only way the water could ascend from the ocean to the mountain tops under pressure- would be through water-tight tunnels. Such tunnels are extremely rare and, even if they did exist in nature, water would escape through the first available hole and flood the entire countryside. Being well satisfied with the validity of his objections to the 'ocean-fed springs' concept, Theory is asked by Practice to fetch any of his Latin philosophers who could possibly present even a single contrary argument!

Palissy did not believe that air could turn into water in the vaults of caverns or cliffs, but he did concede that water could form under such circumstances by the condensation of vapour. But even then, the amounts produced by such a process would be entirely inadequate to provide enough water to sustain river-flows all over the world.

Having thus discarded the two most popular theories of his time, the potter announced his own opinion:

> 'rain water that falls in the winter goes up in summer, to come again in winter, and the waters and the action of the sun and dry winds, striking the land, cause great quantities of water to rise: which being gathered in the air and formed into clouds, have gone in all directions like heralds sent by God. And when the winds push these vapours the waters fall on all parts of the land, and when it pleases God that these clouds (which are nothing more than a mass of water) should dissolve, these vapours are turned into rain that falls on the ground'[35]

This is a more precise concept than was given by most of his predecessors. But questions about what happens after rainfall and how does a river originate still persisted – and Palissy, who knew he was on the right track, was not to be put off:

‘And these waters, falling on these mountains through the ground and cracks, always descend and do not stop until they find some region blocked by stones or rock very close-set and condensed. And then they rest on such a bottom and having found some channel or other opening, they flow out as fountains or brooks or rivers according to the size of the opening and receptacles; and since such a spring cannot throw itself (against nature) on the mountains, it descends into the valleys. And even though the beginning of such springs coming from the mountains are not very large, they receive aid from all sides, to enlarge and augment them; and particularly from the lands and mountains to the right and left of these springs.’[36]

This in a nutshell, said Palissy, is the explanation for the origin of rivers and springs, and no one need seek any other reason than the present one.

Other hydrological concepts

The other hydrological contributions of Palissy, beside the firm declaration about the origin of springs and rivers, were the principles of artesian wells, recharge of wells from nearby rivers, lag in change of water levels in rivers, and forestation for the prevention of soil erosion, and plans for building ‘fountains’ for domestic water supply. The principle of artesian wells was explained casually[37] in a chapter on marl where the potter discussed the exploration and the stratification of soils. Wells of this type were bored in Artois long before his time, but the Huguenot provided a scientific explanation:

‘I think the soil might be pierced easily by rods, and by such means one might easily discover marl, and even well-waters which might often rise above the spot at which the auger found them: and that could take place provided they came from a place higher than the bottom of the hole that you have made.’[38]

He was equally casual on the recharge of wells from waters of nearby rivers. He believed that water in wells near a river came from the river itself. This is justified because the levels of water in such wells are high during periods of high flows but when the river stages fall, so do the levels of water in wells. It conclusively proves that there are ‘veins’ in the earth which extend from the wells to the rivers. If the word ‘vein’ should be changed to bed or aquifer, this statement would express the present explanation of this phenomenon.[39] Palissy was a keen observer of nature, and drew valid conclusions from his observations. He was also a practical man, and a part of the first chapter on waters and fountains from his *Discours admirables* shows his ingenuity in applying the knowledge thus gained to the solution of problems. The problem under consideration in this chapter was how enough water could be obtained for a household situated in a sandy area. Four different cases were given consideration.

The first case had reference to a house located at the base of a mountain. He suggested that all holes and fissures in the mountain side be sealed off so as to reduce leakage to a minimum. The rain water falling within the receiving area can then be guided to discharge at the required point near the base of the mountain which can be accomplished by building walls on both sides. Large stones should be placed across the deeper channels to safeguard the house from the destructive effects of the flash floods which normally occur after heavy rains. As an extra precaution, as well as an investment, trees should be planted on the mountain side, because they will not only slow down the velocity of flow but also will be effective in preventing soil erosion. This is one of the earliest recorded descriptions of the beneficial effects forests have with respect to soil conservation. The water comes down the mountain and passes through two reservoirs, one lower than the other. The upstream reservoir is lined with sand on its uphill side to purify by filtration the water of its undesirable salts. A perforated sheet of metal at the entrance of the second reservoir assures one that only water would enter it. This water could be used for all domestic purposes.

The second case, which was just an extension of the previous one, has reference to a castle, surrounded by a moat, a reasonable distance from a mountain. The plan differs from the first in that the water from the lower reservoir is to be brought to the castle through a series of pipes.

The third case contemplates the building of a reservoir in fiat terrain some distance away from a mountain. The solution to this problem is to select a plot, the size of which depends on the size of the owner's family. That plot is to be given a slope toward the house by shifting soil from one side to another (if necessary), until the difference between the ground levels at the two ends is about four fact. The surface is to be paved with rock, brick, or clay to prevent any loss of water from percolation. Holes can be left in the paving for trees, and the pavement may be covered with about a foot of soil to provide for the cultivation of vegetables. This would be a ‘multi-purpose reservoir' which would provide water, fruits, wood, vegetables, as well as serve as a pasture or a very delightful place to take a walk. It would be very interesting to know if the building of such a reservoir (none has been, so far as the author could find out) would fulfil the potter’s elaborate predictions. While discussing the reason why the seeds sown that way will not be submerged by water in this reservoir, Palissy gives an excellent explanation of the lag in the rise of water levels in rivers:

> ‘Rain water that falls on mountains, lands, and all places that slope towards rivers or fountains, do not get to then so very quickly. For if it were so, all fountains would go dry in summer: but because the waters that fell on the land in winter cannot flow quickly, but sink little by little until they have found the ground floored by something, and when they have found rock they follow its slope, going into the rivers. From this it follows that under these rivers there are many continual springs, and in this way, not being able to flow except little by little, all springs are fed from the end of one winter to the next.’[40]

The fourth and final case was similar to the third except that the owner is unable to afford the cost of paving. It is suggested that under such a circumstance the soil should be packed hard and covered with grassy turf, the closely intertwined roots of which would reduce the percolation losses.

One clear picture emerges from the previous descriptions of building reservoirs, that is: Bernard Palissy observed and tried to emulate nature. The basic fundamental principles underlying the four solutions are exactly the same, i.e., by selecting a gathering ground and reducing its losses due to percolation and evaporation, the maximum amounts of rain water for domestic purposes can be made available to the land owner.

GEORGIUS AGRICOLA

Georgius Agricola (Georg Bauer, 1494–1555) was quite explicit about the origin of ground-water. He, like Aristotle,[41] believed in the creation of water within the earth from the condensation of vapour. Subterranean heat primarily from burning bitumen was the cause of vapourization.[42] His explanation of the process follows:

‘*Halitus* [steam] rises to the upper parts of the *canales* [openings in the earth], where the congealing cold turns into water, which by its gravity and weight again runs down to the lowest parts and increases the flow of water if there is any. If any finds its way through a *canales dilatata* the same thing happens, but it is carried a long way from its place of origin. The first phase of distillation teaches us how this water is produced, for when that which is put into the ampulla is warmed it evaporates [expirare], and this *halitus* rising into the operculum is converted by cold into water, which drips through the spout. In this way water is being continually formed underground.’[43]

Thus, ground-water primarily comes from two sources: infiltration of surface water (rainfall, river and sea), and condensation of subterranean steam which is generated by heating the deeply percolated surface waters. Even though both Agricola and Aristotle believed in the subterranean generation of water, the former was slightly more rational in his concept as he advocated liquefaction of vapour in contradistinction to the Stagirite who preached conversion of air into water. Even then, it was to be admitted, Agricola’s suggestion of vapourization-condensation process was highly unsatisfactory.

The origin of rivers and springs was similarly attributed to the combined effect of rainfall and halitus. The percolation of sea-water landwards was justified by the fact that wells dug near the sea shore frequently yield saline water.

Agricola believed in the use of divining rods for locating minerals or water. This is not very surprising as even men like Robert Boyle (1626-1691), one of the founders of the Royal Society of London who lived nearly a century after Agricola, believed in the effectiveness of the divining rod. The use of the forked twig is described in considerable detail in *De re metallica*, and figure 7 is reproduced from the book. Hoover and Hoover, translators of *De re metallica*, in a footnote state, that:

‘there were few indeed, down to the nineteenth century who did not believe implicitly in the effectiveness of this instrument, and while science has long since abandoned it, not a year passes but some new manifestation of its hold on the popular mind breaks out.’[44]

Ellis[45] has reviewed the use of divining rod for water witching throughout the ages.

Figure 7. Agricola’s concept of the use of divining rods (from *De re metallica*).

JACQUES BESSON

Jacques Besson’s life is something of a mystery, but when he wrote *L’art et science de trouver les eaux et fontaines cachées sous terre*[46] in 1569, he was a professor at Orleans. The small book (only 85 pages) was written in French, and ‘the style has the same fluid character as the subject, a garrulous flow which carries the reader along without much meaning reaching the brain’.[47] The book is divided into three parts; the first part deals with the generation, place, and continuation of water above and below the ground; the second discusses the quantity, depth, and location of underground water. The last part is concerned with the treatment of unhealthy and harmful waters and with methods of conveying water.

Besson believed that at the beginning of the world there were only two elements, water and earth, and that the other two elements, air and fire, were later drawn by attenuation and resolution of a great mass of water which inundated everything. It was, undoubtedly, a biblical outlook because it subscribes to the concept that water covered the entire earth prior to its recession to the depth of the sea and underground.

Besson's main contribution to hydrology was his clear and correct explanation of the hydrologic cycle. He believed that water was evaporated by the heat of the sun, and that it then came down as rainfall. Precipitation is enough to sustain the flows of rivers and springs; evaporation and precipitation are equal in amount. The rivers carry their waters to the sea. His explanation for the salinity of the sea was rather original: it was saline right from the beginning of the creation and hence needed no explanation at all!

He rejected the theory that springs originated in the mountain tops, and stated categorically that springs on the mountain sides are results of precipitation, as can be ascertained by the fact that their flows decrease or increase with the scarcity or abundance of rainfall.

There is considerable controversy over the originality of Besson's work.[47–49] Besson was a contemporary of Bernard Palissy and there are remarkable similarities in the writings of these two Frenchmen, especially with regard to the origin of springs and fountains. The dates of publication of their books are as follows:

1563: Bernard Palissy: Recepte véritable,
1569: Jacques Besson: L'art et science de trouver les eaux et fontaines cachées sous terre,
1580: Bernard Palissy: Discours admirables.

It is significant that neither Besson nor Palissy ever mentioned each other's name in their works. It is possible that Palissy first presented his theory about springs in 1563 and that it was then taken up and elaborated upon some six years later by Besson; then in 1580 Palissy finally returned the compliment. It is very difficult to believe that each of them advanced the same idea without being aware of the other's concept, and it is quite likely that each may have appropriated a large part of the other's views. On the other hand, it is quite possible, especially since both of them were attached to the French court, that Besson and Palissy knew each other. Both were interested in this same subject, and they might well have discussed it together on several occasions. And when the time came to put their thoughts on papers, each may have thought that he was the one who originated the idea. This offers, no doubt, a compromise solution to this problem, but in the absence of better evidence, it would be futile to charge either one as being a plagiarist.

FLOOD STUDY OF GIOVAN FONTANA

The architect Giovan Fontana da Meli carried out investigations of the rise of the Tiber at Rome and the consequent flooding during the Christmas of 1598. The treatise, which was dedicated to Pope Clement VIII, was first published in 1599 and was later reprinted in 1640[50] at the recommendation of Benedetto Castelli. There were numerous controversies over the flooding of the Tiber which, according to Fontana, resulted from man's ignorance of the places and sites where the many different rivers and fosses (canals, ditches, or trenches) entered the Tiber, as well as his ignorance of the effects produced by heavy rainfall and by the sirocco winds, both of which had prevailed for many months prior to the occurrence of the flood. The measurements, on which the study was based, were carried out by Fontana, his nephew, and some 'skilled' men. They systematically traced all of the rivers, torrents, and fosses which flow into the Tiber from Perugia and Orvieto down as far as Rome. Their method was to determine from the depths and the widths of flows in the water courses under normal as well as flood conditions, their wetted cross-sectional areas. Fontana followed the same procedure that the Roman water commissioner, Frontinus had used to determine the discharge through open channels, that is the '$Q = A$' concept (discharge is equal to the wetted cross-sectional area). Thus it can be concluded that after the passage of nearly 1500 years, no improvement had taken place in the technique of measurement of flow in open channels. A sample calculation, and the conclusions of Fontana's investigation are presented below:

'The ordinary running water of the bed of the Chiane River is 72 palms wide and has a depth of water of 8 palms. The Chiane river in the flood which happened at Christmas was 152 palms wide and rose in the flood above today's running water 18 palms ½. Thus discharge during the flood was 152 X 18½ = 2812 square palms (28 ells 12 palms).'

The calculation is divided into 5 parts. water brought in by (1) the river Chiane, (2) the river Paglia, (3) the river Tiber in the place of the Castello di Corbara nearly a mile upstream from the mouth of the Paglia river, (4) the rivers and streams entering the Tiber, from the Corvara to Rome from cast and west sides, and, (5) the river Nera and its tributaries. The final result was as follows:

Total, Paglia river	73 ells 26 palms
Total, Chiane river	28 ells 12 palms
Total, Tiber from Castel della Corvara up to where it begins	135 ells 90 palms
Total, water brought into Tiber rivers and fosses from Corvara to Rome	219 ells 61 palms
Total, river Nera with all its tributaries	42 ells 50 palms
Grand total	500 ells 9 palms

From his investigations, Fontana concluded that the area above Rome contributed to the river Tiber 500 square ells and 9 palms of water more than it normally carried. His recommendation was: 'to eliminate the flood at Rome, it would be necessary to provide two more river beds as ample as the one there is today, at least'.[50]

The solution proposed, in simple words, was channel improvement. The systematic measurement and analysis of flood flow, though conducted under an erroneous concept, undoubtedly turned out to be a praiseworthy effort. No wonder Benedetto Castelli, who in

1628 discussed the full effect of velocity on discharge,[51] recommended that the report of Fontana's investigation be reprinted.

CONCLUSION

The end of the sixteenth century marks the closing of a distinct era in the history of hydrology. Up to that time it was believed that discharge in open channels or pipes was equal to the wetted cross-sectional area. Had the hydrologist of the era expressed this concept mathematically, it would have been '$Q = A$'. It was the same concept that was used many centuries earlier by Frontinus and, it indicates that the methodology for computation of discharge remained the same for more than fifteen centuries. It is true that both Hero and Leonardo had a correct understanding of the phenomenon but, unfortunately, their works, in this particular field, seem to have gone completely unnoticed.

The contributions of Leonardo and Palissy, as far as hydrology is concerned, have one common aspect, that is they did not affect the immediate development of the science. Leonardo's notes were generally not available, and even though Palissy's works were printed, they were in French and, hence probably, did not attract the attention they deserved. According to Pierre Duhem,[52] even the most novel and audacious intuitions of Leonardo had been suggested and guided by the medieval science, and he cannot be regarded as an isolated example who was neither influenced by the past nor had any influence on the future. A similar stand has been taken recently by Bertrand Gille[3] who claimed that Leonardo's works were largely dependent on those of Francesco di Giorgio and other engineers. Duhem further aceused[53] Palissy of being guilty of extensive plagiarism. The originalities of Leonardo and Palissy may be debatable, but it has to be admitted that they were the most outstanding figures of their times in the field of hydrology.

Initially, Leonardo accepted the classical and medieval concept that heat provides energy for elevation, which led him into futile speculations about the origin of rivers and springs – but, he did achieve some results. He was especially lucid in his explanation of continuity, in streams, and his experimental determination of the distribution of velocity in open channels was certainly noteworthy. Palissy can be commended for his views on the origin of springs and rivers, artesian wells, and water resources engineering in general.[54] Both of them opted for experimental methods, but both were equally adept in passing some 'old wives' tales. Undoubtedly their true positions will be somewhere below the statements of hero-worshippers but higher than what the skeptics are willing to admit.

The chapter can best be concluded with a quotation from Leonardo:

'Wisdom is the daughter of experience ... No human enquiry is worthy of the name of science unless it comes through mathematical proofs. And if you say that the sciences which begin and end in the mind possess truth, this is not to be conceded, but denied for many reasons. First because in such mental discourses there enters no *esperienza** without which nothing by itself reaches certitude.'

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* Wavers in meaning between experience and experiment.

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