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Beginning of quantitative hydrology

INTRODUCTION

Towards the end of the seventeenth century, nearly all investigators of distinction belonged to one scientific society or another. The most notable of those societies were the Royal Society of London, and the Académie Royale des Sciences of Paris, founded in 1662 and 1666 respectively. Publishing the results of new investigations in journals of the societies was a logical occurrence, and the two societies gradually attained a prestige greater than that of most universities.

Three men of this period are particularly outstanding for their contributions to the development of the science of quantitative hydrology. All three were connected, directly or indirectly, to both of those societies. They were the French naturalist Pierre Perrault; the French physicist, Edmé Mariotte; and the English astronomer, Edmond Halley. As quantitative hydrologists, they were the first to undertake experimental investigations to establish some of the fundamental principles in that science. Mariotte and Halley, members of the Académie Royale des Sciences and the Royal Society respectively, played significant parts during the early years thereof, and although Perrault did not belong to either of those scientific societies, his brother, Claude, was an active member of the French Academy, and Christiaan Huygens (1625–1695), the physicist, to whom his book *De l'origine desfontaines* is dedicated, was considered a mainstay of the Academy. In any event these three scientists, Perrault, Mariotte, and Halley, for the first time in history, started the science of hydrology off on a quantitative basis.

PIERRE PERRAULT

Only a little is known about the personal life of Pierre Perrault (1608–1680). Following his father's footsteps, he became a lawyer. He bought the post of receiver-general of finances for Paris, but bund it necessary to help himself from the treasury to satisfy his creditors. He was caught while performing that offense, and was dismissed by Colbert who was then at the height of his power. Pierre vas rather overshadowed by his three younger brothers: Nicolas (1611–1651), a noted theologian; Claude (1613–1688), a physician, scientist, and the architect of the Louvre; and Charles (1628–1703), a critic, and the author of the Mother Goose fairy tales. Claude became an important figure in the history of science, and was undoubtedly one of the most eminent scholars of his time. In 1673, he translated Vitruvius' work on Architecture.

The book, *De l'origine des fontaines*[1] (The origin of springs), was published anonymously in Paris, in 1674, and was dedicated to 'Monsieur, Mr. Huguens de Zulichem'. The authorship of the book has been the subject of considerable controversy in the past, and has been attributed variously to André Félibien, Denis Papin, and finally to its true author, Perrault. The first originated with an erroneous classification in the catalogue of books in the Aguesseau Museum (No. 3297); and the second in the Philosophical Transactions of the Royal Society, where a review of the book first appeared under the following heading: 'A particular account given y an anonymous French Author in his book on the Origin of fountains printed in Paris in 1674 to show that the Rain and Snow Waters are sufficient to make Fountains and Rivers run perpetually'.[2] That review appeared in 1809 in an abridged edition of the Transactions where the name of the author was given as Denis Papin. Figure 1 is reproduced from the original 1674 edition.

Figure 1. The frontispiece from Perrault's *De l'origine des fontaines*.

The work is presently attributed universally to Perrault,[3, 4] and is so listed in the catalogues of the British Museum, the Bibliothèque Nationale, and the Library of Congress. In a further confirmation thereof, it was found that N. A. Félibien had written Perrault's name as its author in a first edition thereof which had been presented to him 'Du don de l'autheur, ce 23 octobre 1674'. That copy, incidentally, was sold in Paris in 1872.[5] An excellent investigation into the authorship of the book has been published in an article by Dooge.[6] Perrault's book on the origin of springs was initially written just for private circulation among his friends, but because of its importance he was persuaded to have it published. In it he reviewed the various propositions of the previous authors on the subject (demolishing their conclusions in most cases), and he proposed that an experimental investigation be performed to prove that rainfall alone is sufficient to support the flow of springs and rivers throughout the year. Parts of the book had been translated previously,[2, 6, 7] but it was not until 1967 that the entire work was brilliantly translated with annotated references, by Aurèle La Rocque.[3]

Perrault's proposition was simple:

'It would be necessary, to attain our goal, to measure or estimate the water in some river as it flows from its source to the spot where some brook joins it, and see if the rain water that falls around its bed when put into a reservoir, as Aristotle says, would be sufficient to cause it to flow for a whole year. I have seen the Seine River, and have examines it rather closely in its course from its source to Aynay le Duc, where a brook joins and enlarges it: that is why I shall take it as the subject of the examination I wish to make.

The course of this young River from its source to Aynay le Duc is about three leagues long, and the slopes of its bed extend to right and left about two leagues on each side, where there are other brooks that flow elsewhere; and since these brooks need rain water for their subsistence as much as the Seine, I wish to count only one half of this space of the sides, and say that the area where the Seine flows, is from its source to Aynay le Due three leagues long by two leagues wide, and then I shall argue as follows. [The catchment area studied is shown in figure 2.]

If a reservoir had been made with this length and width it would be six square leagues in areas, which when converted to toises [about 6 ft] according to the measurements already established, would make 31,245,144 toises in area.

Into this reservoir we must imagine that rain has fallen for one year to the height of 19⅓ inches* which is the height of an average year, as we have noted. This height of 19⅓, inches gives 224,899,942** muids of water or approximately, according to the measure we have agreed upon.

All this water thus accumulated in the quantity just mentioned is what must be used to cause this River to flow for one year, from its source to the place designated, and which must serve also to supply all the losses, such as the feeding of trees, plants, grasses, evaporation, useless flows into the River which swell it for a time and while it rains, turning away of waters which can take another course than that towards this River because of irregular and opposite slopes, and other such wastes, losses, and reductions.

As to the measurement or estimation of the water of this young river, it would be hard to find it exactly and to say what quantity it furnishes: Nevertheless as far as I have been able to judge it

* The French inch (pouce or poulce) was divided into 12 lines, and was equal to 27 mm.

** The muid of Paris was equal to 24 hectolitres for salt, and to 268 litres for wine. The latter is probably closest to Perrault's measure.

cannot have more than 1000 to 1200 inches always flowing, compensating for less at its source with more which it has towards Aynay le Duc, which I judge by the comparison I make of these waters with those of the Gobelins River as it is near Versailles where it has 50 inches of water according to measurements made of it: thus I estimate that it will be enough to give 24 or 25 times as much to ours: for its bed is only four or five toises wide, its depth is small, it will not float boats, and serves only to carry logs which are thrown into it singly to be tied together lower down and to make them into floating log rafts.
Having thus supposed all these things, I say that according to the measurements we have agreed upon, 1200 inches of water give in 24 hours, on the basis of 83 muids of water per inch, 99,600 muids of water; and during one year which is 366 times as much, they will give 36,453,600 muids. This River therefore carries within its banks from its source to Aynay le Duc during one year only the said quantity of 36,453,600 muids of water. But if I draw this quantity of water from the 224,899,942 muids, which are in this reservoir which we have just imagined, there will still be left, 188,446,342 muids, which amounts to almost five times as much, and serves for the losses, decreases and wastes which we have noted. Only about one-sixth part of the rain and snow water that falls is therefore needed to cause this river to flow continually for one year.
I know very well that this deduction has no certainty: but who could give one that would be certain? Nevertheless whatever this one may be, I believe it is more satisfactory than a simple negative like Aristotle's and that of those who maintain, without knowing why, that it does not rain enough to supply the flow of rivers. However that may be, until someone makes more exact observations, by which he proves the contrary of what I have advanced; I shall hold to my view, and be content with the feeble light shed by the observation I have made, being unable to have a stronger one.
If then these waters are enough for the flow of one River, they will suffice for all the other Rivers of the World in proportion, having regard mainly to what is left for wastes, which is more than enough, and to the little space I have allotted on each side of the bed for the River which is only one league on each side: for Rivers are not usually only two leagues apart. It is therefore likely to say, that the waters of rains and snows are sufficient to cause the flow of all the Rivers, of the World.'[8]

Perrault, however, did not believe in general infiltration of rain water and thereby recharge of ground water. He went to great lengths to find evidence of general infiltration, and from his observations he concluded that it was an occasional and local phenomenon. In the beginning of the second part of this book, Perrault differentiates his own view from that held by Vitruvius, Gassendi, Pallisy and Francois which he called 'general opinion'. He objected to their concept of infiltration of rain water into the earth, and said that he did not believe that there was just enough precipitation to soak the earth as much as necessary, and then a sufficient quantity was left over to cause rivers and springs. Thus, the two opinions may be compared as follows:

general opinion: rain → infiltration → springs → rivers,
Pierre Perrault: rain → rivers → springs.

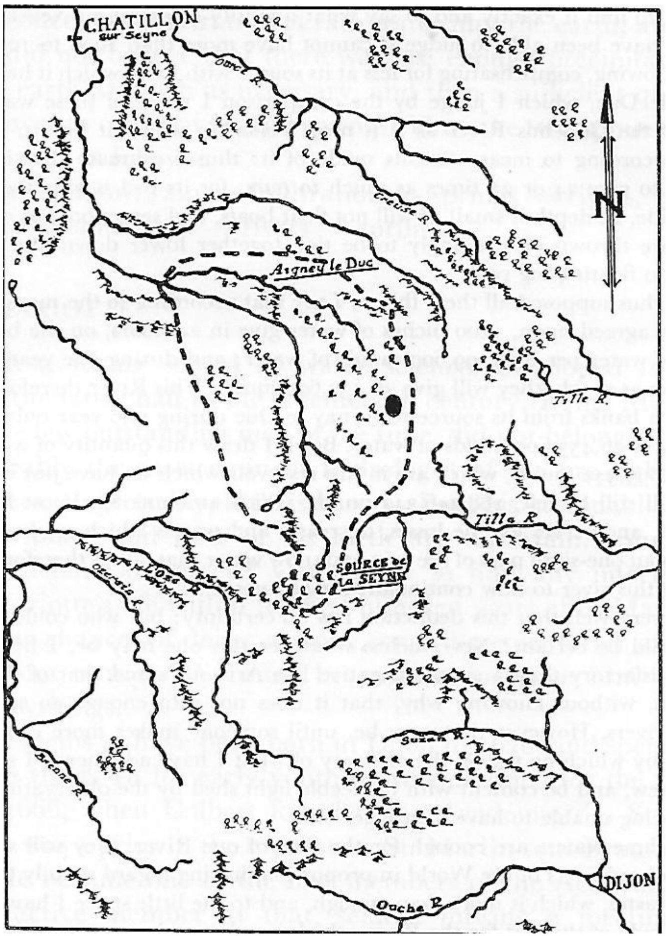

Figure 2. The catchment area studied by Perrault (by courtesy of James C. I. Dooge).

EDMÉ MARIOTTE

Although a strong school in water sciences developed in Italy towards the latter half of the seventeenth century, Edmé Mariotte, one of the few outstanding men of the time, did not belong to it. He was probably the most eminent hydrologist of the pre-eighteenth century era. Regrettably, little is known about his personal life, and even the place and date of his birth are uncertain.[9] Since the mathematician Condorcet[10] was unable to find any information about Mariotte's life within the first hundred years after Mariotte's death, our chances of doing so now, some three centuries after his death, seem remote. We must be content to judge him merely from his writings.

Mariotte seems to have been born in Dijon in 1620, and spent most of his life there. In his early youth he was destined for the clergy, and in 1666, when Colbert founded the Académie des Sciences, Mariotte was a prior in the monastery St. Martin-sous-Beaune near Dijon. He became one of the first members of the Academy, and was an active member at that, seldom missing a meeting. He pursued scientific investigations into a great variety of subjects, with great zeal, which suggests a probability that he could not have spent much time at his duties as a prior. He presented papers to the Academy on many subjects including notes of the trumpets, the recoil of guns, the nature of colour, and motion of fluids. Perhaps his greatest contribution to science was the Boyle-Mariotte law, which states that the volume of a given mass of gas varies inversely with the impressed pressure.

His works on hydraulics and hydrostatics, presented before the Academy in 1669 and published posthumously in 1717, had a considerable bearing on the later development of hydraulics and hydrology. During the early days of his final illness, Mariotte gave the manuscript of his book *Traité du mouvement des eaux et des autres corps fluides* to his learned friend Phillipe de la Hire. De la Hire was given full responsibility to finish and edit the manuscript, and he did so admirably. The book was published in 1686. It was translated into English, in 1718, by Rev. J. T. Desaguliers, one of the several men who supported the syphon theory for the ebbing and flowing of springs.

Mariotte died in Paris on May 12, 1684 – the year in which he had clearly demonstrated by his experimental investigations that rainfall was the source of water discharged by springs and rivers.[11]

According to Condorcet 'the upright and disinterested love of truth displayed by Mariotte is excelled by very few investigators',[10] and Rühlmann, in his book on mechanics,[12] expressed the belief that Mariotte's work presented the first worthwhile measurements of velocity of flowing water.

Figure 3 is a copy of probably the only surviving picture of Mariotte.[13] The enlargement of the central portion (figure 4) shows four distinguished men of the era – Louis Gayant, Edmé Mariotte, Claude Perrault, and Jean Pecquet.

Figure 3. The Académie Royale des Sciences at work in the Royal Library, Paris, in 1671. Edmé Mariotte is one of the central figured in skullcap and spectacles (from a vignette by Sébastien Le Clerc).

Treatise on the motion of water

Mariotte's book on the motion of water and other fluids[14–16] was divided into the following five parts:

(1) several properties of fluid bodies, the origin of fountains, and the causes of winds;
(2) the equilibrium of fluids by their gravity, impulse and spring;
(3) running and spouting water and their measurements;
(4) the heights of perpendicular and oblique jets and of their amplitudes; and
(5) the conveyance of water and the resistance of pipes.

Of special interest to hydrologists are the causes of origin of springs (part 1, chapter 2), the determination of velocities of running water at the surface and at the bottom (part 2, chapter 3), and the measurement of discharge in a river or an aqueduct (part 3, chapter 4).

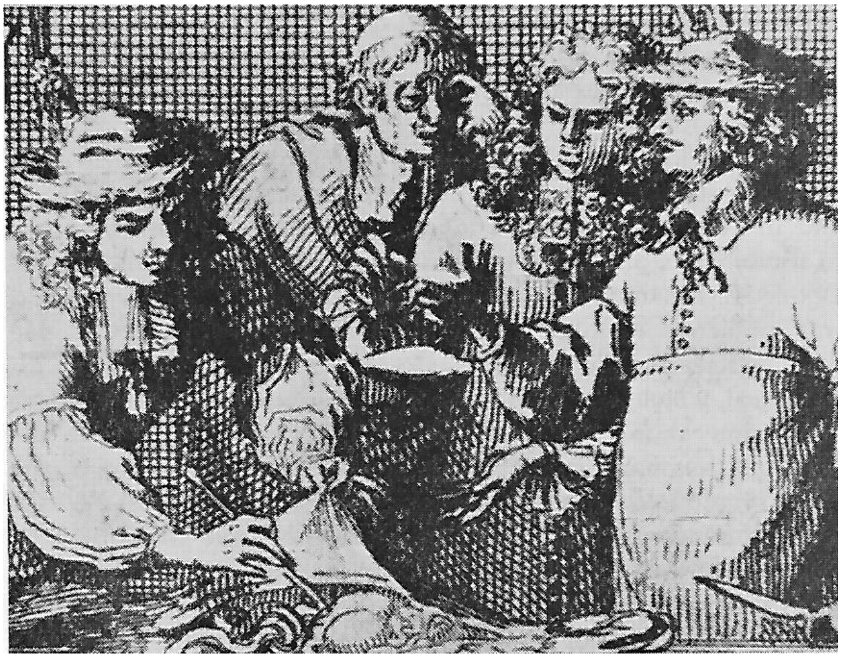

Figure 4. Enlargement of the central group in figure 3. From left to right are Louis Gayant, Edmé Mariotte, Claude Perrault and Jean Pecquet.

Origin of springs

Mariotte claimed that rainfall was more than adequate for the creation of springs and rivers, and in this concept he was probably influenced by Perrault's work. Percolation takes place after precipitation. When rainfall occurs on hills and mountains, it penetrates the surface of the earth, particularly when the soil is light and mixed with pebbles and roots of trees. Then, if it encounters a layer of clay or a bed of continuous rock, which it is unable to infiltrate, it flows along the surface thereof until it finds a point of egress either at the bottom of the mountain or at a considerable distance below the top.

There it breaks out as a spring. Besides proving by experimental investigations that the amount of water that falls as rain is more than enough to supply all the springs and rivers, he demonstrated that the increase or decrease in the flow of springs is directly related to the amount of precipitation. If it does not rain for two months, most streams lose half of their flow, and when a rainless condition continues for a year, most of them become dry. The few which continue to flow do so with a greatly reduced discharge. Mariotte did not believe in the hypothesis about condensation taking place in vast vaults within mountains, and explained why such an occurrence was impossible:

'For if ABC [figure 5] is a vault in the mountain DEF; it is evident, that if the vapours should become water in the concave of the surface ABC, that water would fall perpendicularly towards HGI, and not towards L, or M, and consequently would never make a spring: Besides, it is deny'd that there are many such hollow places in mountains, and it can't be made appear that there are such. If we say there is earth on the side of, and beneath ABC, it will be answered, that the vapours will gush out at the sides towards A, and C, and that very little will become water; and because it appears that there is almost always clay where there are springs, it is very likely that those supposed distilled waters can't pass through, and consequently that springs can't be produc'd by that means.'[17]

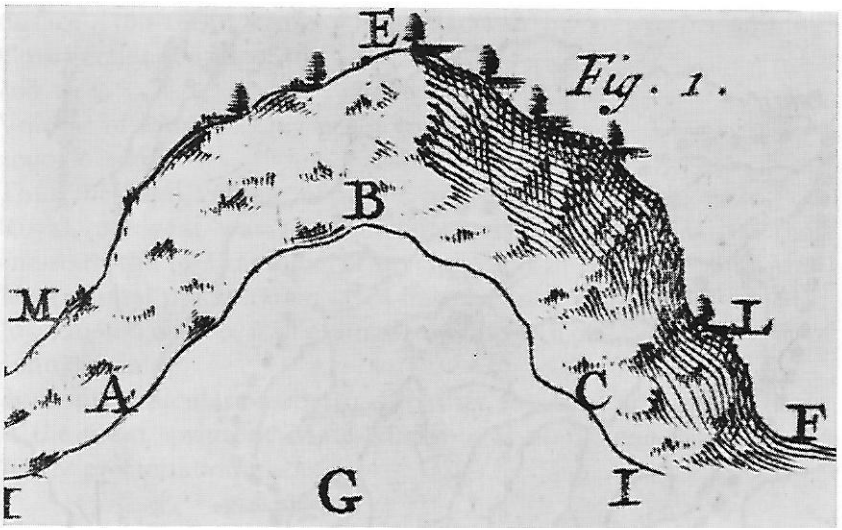

Figure 5. Mariotte's sketch of a mountain vault.

Mariotte measured the total annual rainfall at Dijon as part of his demonstration showing that rainfall was adequate to supply the water flowing in streams and rivers. The observations were taken very skill fully according to his directions, and the annual precipitation was found to be 17 in. After comparing it with the total of 19 in., $2\frac{1}{3}$, lines, observed by Perrault, he selected a conservative value of 15 in. for use in his calculations. Keilhack[18] states that Mariotte had determined the rainfall at Dijon for three years, and had found the average annual rainfall to be 19 in., $2\frac{1}{3}$ lines (the same result that Perrault had obtained). A possible explanation for that seemingly strange coincidence, as Dooge[6] has pointed out, is that the value came from a misreading of Mariotte's book, rather than from a knowledge of Perrault's experiments.

Mariotte's calculation was:

15 in. of annual rainfall = 45 cu. ft water/square fathom/year
Assume 1 league = 2300 fathoms,
Therefore rainfall per square league per year is
= 2300 X 2300 X 45
= 238,050,000 cu. ft.
The catchment area of the river Seine near Paris (figure 6) was assumed to be 60 leagues long by 50 leagues wide. Thus the total annual rainfall on the catchment area was:
= 60 X 50 X 238,050,00
= 714,150,000,000 cu. ft.

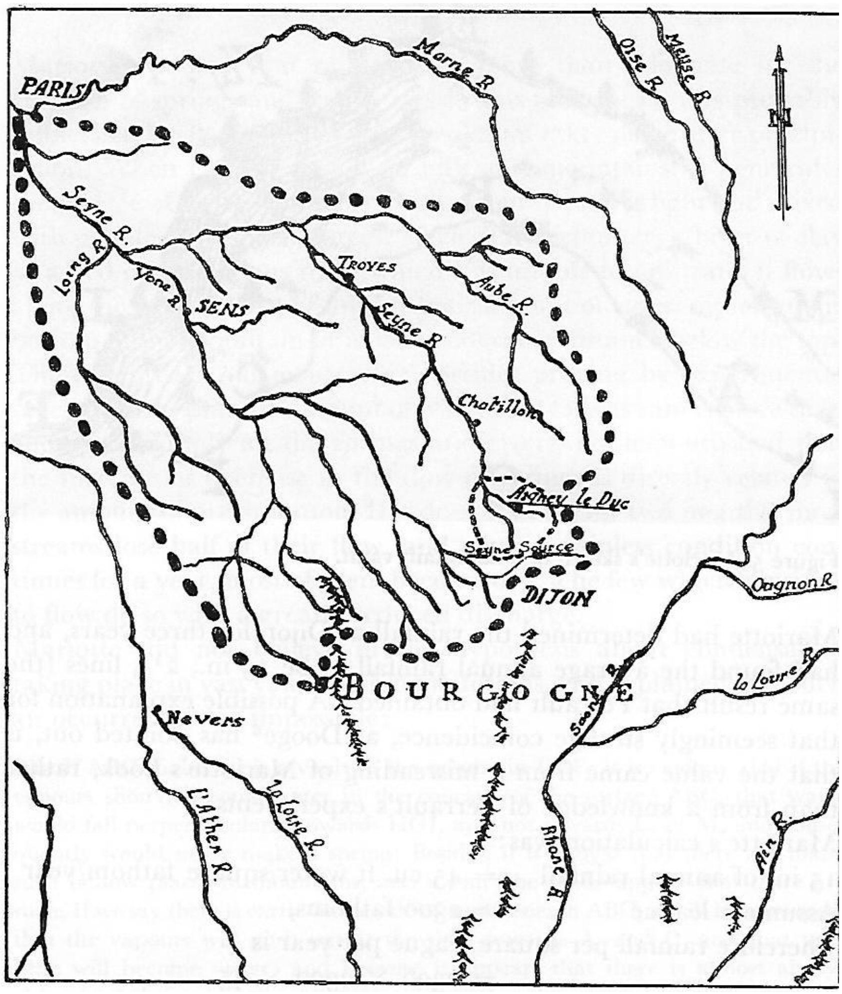

Figure 6. The catchment area studied by Mariotte (by courtesy of James C. I: Dooge).

The discharge in the river Seine was determined near Pont Royal. The width of the river was taken to be 400 ft, but as the depth varied from 10 ft to 2 ft, the mean depth was taken to be 5 ft. Mariotte found that 'when the waters were at their greatest height', a float placed in the middle of the river had the same velocity as a man walking very fast which was equivalent to 15,000 ft Per hour or 250 ft per minute. The velocity at the mean depth was found to be 150 ft per minute, and since 'the bottom of the water does not go so swiftly as the middle, nor the middle so fast as the upper surface', the mean velocity was taken to be 100 ft per minute.

Cross-sectional area of the Seine:

400 X 5 = 2000 sq. ft.
Volume of water passing per minute:
2000 X 100 = 200,000 cu. ft.

Thus the total volume of water passing in the Seine, near Pont Royal, per year was 105,120,000,000 cu. ft. This was less than one-sixth the total amount of precipitation in the catchment area. If an annual precipitation of 18 in. were used instead of 15 in., the 105,120,000,000 cu. ft of annual runoff to 856,980,000,000 cu. ft. of annual rainfall.

By similar calculations he showed that the total annual discharge of the great spring at Mont-Martre was about one-fourth of the yearly precipitation.

Discharge determination

Like Leonardo da Vinci and Benedetto Castelli, Mariotte used floats to determine velocities in open channels. He suggested that a ball of wax be used as a float with something heavy inside to submerge it in water as deeply as possible, without sinking. The primary reason for such a measure was to reduce as much as possible, the effect of wind on its travel. The speed of the float over a reach of 15 ft to go ft was timed with a half-second pendulum. To calculate the discharge, he suggested that one 'multiply the breadth of the aqueduct by the height of the water, and the product by the space which the wax shall have run thro'. The last product which is solid, will give all the water which shall have pass'd during the time of observation'.[19] He emphasized that such calculations assume that the velocity of water to be the same at its top, bottom, and sides. Probably Mariotte was the first man to realize that water surface should have the same inclination as the river bed if accurate results are to be obtained.

He presented an example to indicate the manner of calculating the mean velocity of an aqueduct having a cross-sectional area of 2 ft by 1 ft. The float was carried 30 ft in 2o seconds, but since velocity is greater at surface than at bottom, the mean velocity was taken to be 20 ft in 20 seconds. It is interesting to note that in all his calculations Mariotte used a mean velocity which was two-thirds of the surface velocity. The unit, inch, was also used for expressing discharge. This was defined as 'the quantity of water which runs thro' a circular hole of an inch diameter, vertically made in one of the sides of a vessel, when the surface of the water, which supplies the running out, always remains at the height of one line above the hole'.[20]

Discharge of the aqueduct was calculated by:

Cross-sectional area = 2 X 1 = 2sq. ft.

Discharge per 20 seconds = 2 X 20 = 40 cu. ft

= 40 X 35 = 1400 pints

(1 cu. ft = 35 pints of water)

Hence discharge per min. = 1400 X 3 = 4200 pints

$$= \frac{4200}{14} = 300 \text{ in.}$$

Mariotte used interconnected floats to demonstrate that the velocity at the bottom was less than at the surface. He used two wax balls interconnected by a 1-ft string, the lower ball filled with stones, so that when placed in water it dragged the lighter ball down until the upper part was just even with the water surface. In a 3-ft deep river, he found that the lower ball always lagged behind. But in places of local constrictions, the lower ball travelled faster than the upper one. He explained the phenomenon as shown in figure 7. Assume that ABCD (figure 7) was the elevation of the original water surface. Due to the presence of a constriction near B, water level rises to the dotted line EF. Obviously water would run faster along the steep declivity EFC, and owing to the higher velocity thus attained, it would continue along GH which means that velocity at G and H would be higher than at I and D. This was also the reason, he explained, for the formation of great cavities just downstream from bridge piers.

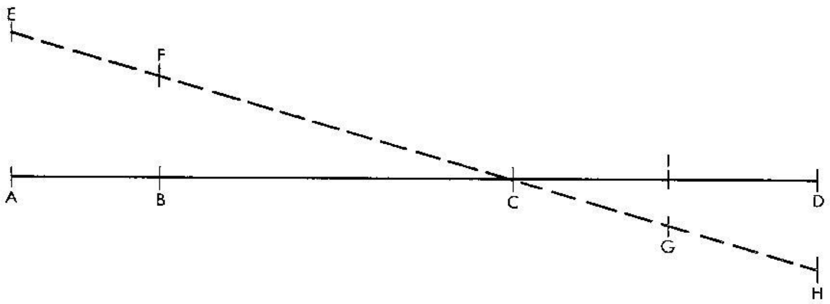

Figure 7.

EDMOND HALLEY

Edmond Halley (figure 8), the eldest child of a rich salter, was born in London in 1656. He was educated at St. Paul's School and Queen's College of Oxford University, but did not finish his course of studies. His first paper (in Latin) on planetary orbits was published in the Philosophical Transactions of the Royal Society before he even reached the age of twenty. He sailed for St. Helena in November 1676, with one of his fellow-undergraduates,[21] to observe the southern stars, having the full consent of his father who gave him a generous allowance of £ 300 per year – more, perhaps, than he ever earned in his life.[22] St. Helena was chosen because it was the southernmost of the English colonies. There he catalogues the latitudes and longitudes of 341 stars, grouped by constellations.[23]

He also made numerous pendulum observations and was the first man to record the complete transit of the planet Mercury. On his return from the island, King Charles the Second persuaded Oxford University to grant him the Master's degree without his having residential qualifications or even taking examinations. In 1678, at the age of 22, he was elected a fellow of the Royal Society.

In August 1684, he met Newton, and it was the beginning of a life-long friendship. The following year he resigned the Fellowship of the Royal Society to become its clerk, a post he held till 1698, when he joined the Navy as a Captain to conduct the first British expedition to study Antarctic icebergs and penguins. He was appointed the Savilian Professor of Geometry at Oxford, in, and nine years later, became the Secretary of the Royal Society. At the age of 64, in 1720, he succeeded Flamsteed as the second Astronomer Royal. He was elected a foreign member of the French Academy of Sciences in 1729, and died in 1742.

Edmond Halley, undoubtedly, was a versatile genius. Primarily known as a pioneer in astronomy, geophysics, and mathematics, he was interested in subjects such as history, archaeology, navigation, and civil engineering. He wrote poems in Latin, translated books from Arabic and Greek, and was the founder of population and actuarial statistics, and a co-founder of experimental hydrology.

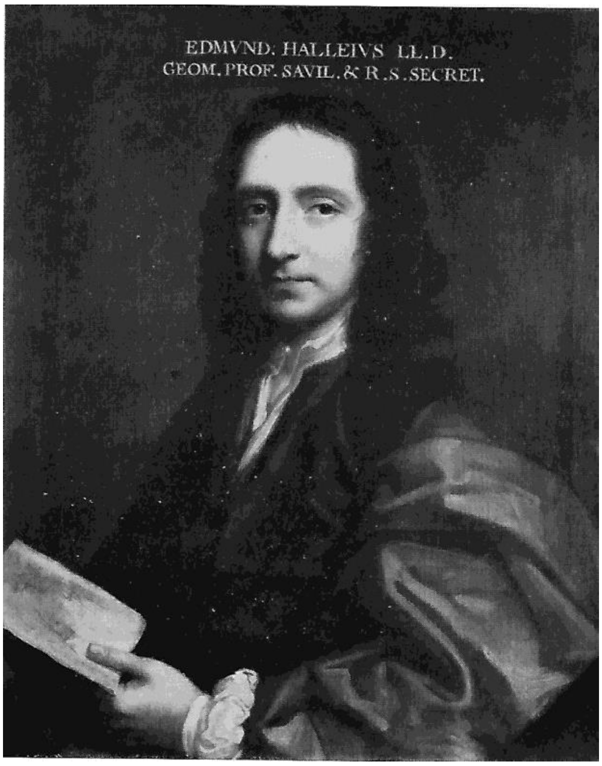

Figure 8. Edmond Halley, a portrait by Thomas Murray (by courtesy of the Royal Society of London).

Experiments on evaporation

'Men of Gresham' was the name given to the fellows of the Royal Society of that time,[24] whose meeting place was at the Gresham College (figure 9). It was here that Halley conducted his well-known experiments in evaporation. The results were reported in a series of four papers published in the Philosophical Transactions of the Royal Society in 1687, 1691, 1694, and 1715 respectively.

Halley's work on evaporation may well have been motivated by the experiments of Perrault and Mariotte. Both of their books were reviewed in the Philosophical Transactions of the Royal Society[2, 15] and Halley may have decided to try to prove the remaining half of the hydrological cycle, i.e., that enough water evaporates from the oceans and the water courses to produce the rain for replenishing the flow of rivers. Be that as it may, his interest in the evaporation phenomenon was first aroused when he was on the island of St. Helena. His celestial observations were generally taken at night on tops of hills about 2400 ft above sea level. He found, to his great annoyance, that there was such a heavy condensation of vapour when the sky was clear, that he had to wipe his lenses every few minutes and also had trouble in recording his observations because the paper became so wet that ink could not be used. After his return from the expedition, he undertook to explain the ‘grand phenomenon’ of the equilibrium of the sea ‘which is so justly performed that in many hundreds of years we are sufficiently assured that the sea has not sensibly decreas’d by the loss of vapour; nor yet abounded by the immense quantity of fresh water it receives continually from the rivers’.[25]

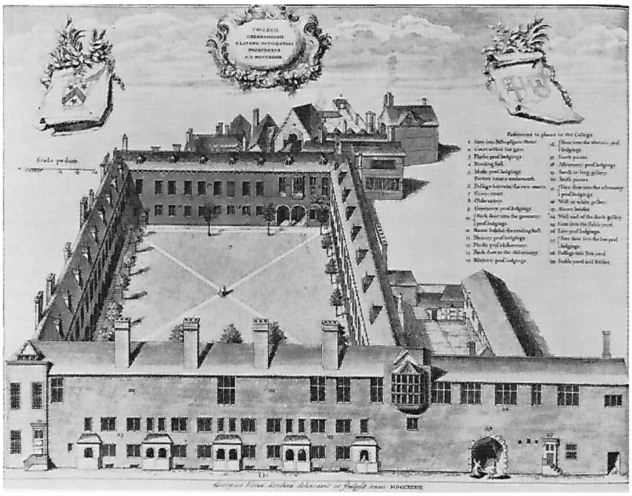

Figure 9. Gresham College, the birthplace and early home of the Royal Society of London, where Halley’s evaporation experiments were conducted. From a painting by George Virtue, 1739 (by courtesy of the Society of Antiquaries, London).

Halley’s explanation of the process of evaporation was that if an ‘atom of water’ was heated so that it expanded to become a bubble ten times its original diameter, it would become lighter than air, and would consequently rise upwards. With additional heat, more and more particles of water became separated and were emitted with a great velocity, as could be seen in case of boiling cauldrons. The sun heats up the air during the day, and also raises ‘more plentiful vapours from the water’. Warm air is capable of holding more aqueous vapour than cool air, and hence during the night when it becomes gradually cooler, some of the vapour is changed to dew. The process is somewhat analogous to the fact that warm water can dissolve more salt than cold water; but when the temperature of the solution drops, some of the dissolved salt is precipitated.

Halley suggested that:

‘Those vapours therefore that are raised copiously in the sea, and by the winds are carried over the low land to those ridges of mountains, are there compelled by the stream of the air to mount up with it to the tops of the mountains, where the water presently precipitates, gleeting down by the crannies of the stone; and part of the vapour entering into the caverns of the hills, the water thereof gathers as an alembick into the basons of stone it finds, which being once filled, all the overplus of water that comes thither runs over by the lowest place, and breaking out by the sides of the hills, forms single springs.’[25]

The springs unite to form rivers which carry the water back again to the sea. Figure 10 is an illustration of Halley’s concept of the hydrologic cycle from an early eighteenth century book by Switzer[26] on hydraulics (probably the first English work bearing the title 'hydraulics' – a term introduced by Robert Boyle). Switzer, incidentally, disagreed completely with both Halley's and Mariotte's concepts on these subjects.

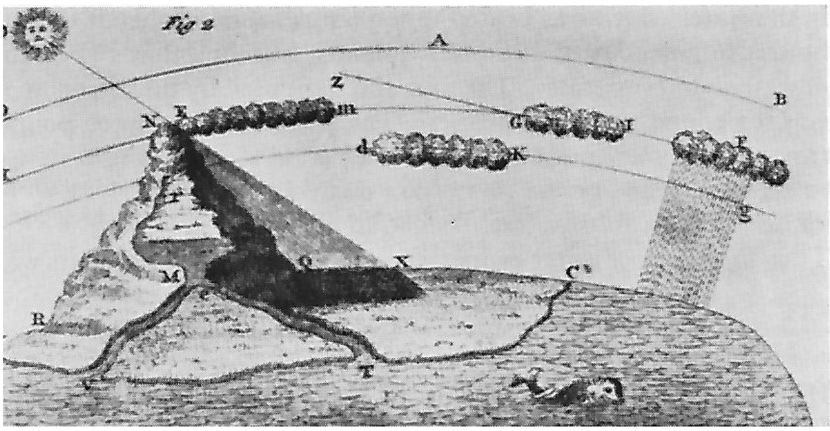

Figure 10. Halley's theory of springs and seen by Switzer.

Evaporation and the origin of springs

There was a fundamental difference between the explanations of the French scientists and the English astronomer on the origin of springs. Perrault and Mariotte concluded that springs originated from intermittent rains, but Halley stated that water is being continually condensed out of vapour on the long mountain ridges, and: 'it may almost pass for a rule, that the magnitude of a river, or the quantity of water it evacuates is proportionable to the length and height of the ridges from whence its fountains arise'.[25]

In a later paper[27, 28] presented to the Royal Society, Halley demonstrated that enough evaporation takes place from the oceans to more than replenish all springs and rivers. To determine the amount of water evaporating from the oceans, he took a pan of water, 4 in. deep and 7.9 in. in diameter. A thermometer was placed in the water which was heated to the temperature of the air 'in our hottest summer'. At the end of two hours, he found that 233 grains of water had evaporated. The unit of weight used by the astronomer was the pound troy, now obsolete. The relationship between pound troy and ordinary pound (avoirdupois) is:

1 oz troy = 480 grains = 1.09714 oz avoir, and
12 oz = 1 lb troy = 0.82286 lb avoir.

Thus the depth of water evaporating from the pan in two hours was:

$$\frac{233 \times 76}{1726} \times \frac{1}{49} = \frac{1}{53} \text{ in.}$$

He assumed that 1 cu. ft of water weighs 76 lb troy, and credited Edward Bernard of Oxford for its determination. To simplify subsequent calculations, the depth of evaporation from the pan was taken as 1/120 in. per hour. He considered that the evaporation took place in summer for 12 hours per day, because 'dews return in the night, as much if not more vapours than are then emitted'. Halley calculated that if the Mediterranean Sea was assumed to be 4 degrees (1 degree = 69 miles) long and 4 degrees broad, the total amount of water lost from the sea by evaporation per summer day would be 5,280,000,000 tons. He went on to say that the figure arrived at was very conservative because evaporation depends to a great extent on wind, and its effect was totally neglected in his calculations.

Halley next calculated the amount of water the Mediterranean received from the nine major rivers – Iberus, Rhone, Tiber, Po, Danube, Neister, Borysthenes, Tanais, and Nile. If the river Thames had a cross-sectional area of 300 ft X 9 ft and a mean velocity of 2 mph, the total flow per day would be 20,300,000 tons. Assuming each of the above nine rivers had a discharge equal to ten times that of the Thames, total fresh water received by the Mediterranean per day would be 20.3 X 10 X 9 = 1,827,000,000 tons. Because it is slightly more than one-third the total loss of water, it was proved hat enough water evaporated from the ocean to supply all the streams and rivers.

Halley had a reasonably clear conception of the hydrologic cycle:

'Thus is one part of the vapours blown upon the land returned by the rivers into the sea, from whence they came; another part by the cool of the night falls in dews or else in rains; again into the sea before it reaches the land, which is by much the greatest part of the whole vapour, because of the great extent of the ocean, which the motion of the wind does not traverse in a very long space of time. And this is the reason why the rivers do not return so much into the Mediterranean as is extracted in vapour. A third part falls on the lower lands, and is the pabulum of plants, where yet it does not rest, but is again exhaled in vapour by the action of the sun, and is either carried by the winds to the sea to fall in rain or dew there, or else to the mountains to be there to be turned into springs; and though this does not immediately come to pass, yet after several vicissitudes of rising in vapour and falling in rain or dews, each particle of the water is at length returned to the sea from whence it came. Add to this that the rain-waters, alter the earth is full sated with moisture, does by the valleys or lower parts of the earth find its way into the rivers, and so is compendiously sent back to the sea. After this manner is the circulation performed…'[25]

In the third paper[29] of the series, Halley describes the investigation carried out in the Gresham College by Henry Hunt 'with great care and accuracy', under his direction in 1693. The evaporation from a screened and sheltered water surface (having a surface area of 8 sq. in.) was noted every day for the year 1693. Also recorded were temperature (outside?), pressure, and general precipitation conditions (snow, rain, or frost). All observations were taken at 8 a.m.

The total annual evaporation was 64 cu. in., or 8 in. of water per sq. in. of the area. He compared it with Perrault's recording of 19 in. of annual rainfall in Paris and Townley's 40 in. at the foot of the hills in Lancashire, but evidently the water evaporated was too little to account for the total annual precipitation. His explanation, for the residual evaporation required to balance the rainfall, was that the direct effects of the sun and wind had been excluded in his experiment. He concluded that the wind effect would have increased the evaporation at least three times, and the sun perhaps might have doubled it.

The experiment also indicated that the evaporation during the months of May, June, July and August are approximately equal, and are about three times the monthly evaporation occurring during November, December, January, and February, and twice as much as that of March, April, September, and October. Regrettably, Halley does not mention anything about the container of water from which evaporation took place. Probably it was a 'pan of water' – like the one used for his previous evaporation experiment, and was filled to the top every morning at 8 o'clock.

The final paper[30] of the series appeared in 1715, and is of considerable interest to all historians of science. Halley considered four closed-in (i.e., having no outlet) seas and lakes – Caspian Sea, Dead Sea, Lake of Mexico, and Lake Titicaca in Peru. He reasoned that as these lakes and seas have no exits, but receive water continuously through various rivers, the levels should rise 'until such time as their surfaces are sufficiently extended, so as to exhale in vapour that water that is poured in by the rivers'. He suggested that as the rivers are continually carrying dissolved salt to the ocean, and the loss through evaporation is only of fresh water, the salinity of the sea must be steadily increasing. Halley concluded that from the degree of salinity, it would be possible to estimate the age of the earth.

CONCLUSION

A study of the development of the science of hydrology will clearly indicate that there have been numerous early contributors to applied hydrology but that their experiments were isolated. Only during the seventeenth century there was a concerted attempt made to establish some fundamental hydrological principles on an experimental basis.

The major contributors of that period were Pierre Perrault, Edmé Mariotte, and Edmond Halley. Their contributions to the development of hydrology are truly incalculable. It was Perrault who proved, for the first time by experimental investigations, that rainfall is adequate to sustain stream-flow. His concept of the pluvial origin of springs may have been considerably influenced by Father Jean François (1582–1668) who taught in several Jesuit colleges, and wrote extensively on hydrogeology. His book *La science des eaux qui explique en quatre parties leur formation, communication, mouvements et mélanges*,[31] first published in 1653, was certainly known to Perrault. The opinions of Father François and Perrault on the origin of springs are certainly very similar but unless a thorough study of the Jesuit's works is undertaken it would be impossible to evaluate his influence on Perrault.

Perrault's work was widely known among scientific circles in the seventeenth century, but the posthumous work of Mariotte enjoyed more respect primarily because Mariotte was the more outstanding scientist of his time. Both books, however, received considerable opposition particularly with respect to their concepts of the hydrologic cycle. In fact, with regard to his views on that subject, Perrault could not even convince his brother, Charles, who, along with De la Hire, conducted the following simple experiment in 1690. They buried a clay vessel at a depth of 8 ft and later at 16 ft below the surface and connected it by means of a lead pipe to a cellar. Since no water was discharged from the pipe, it was concluded that rain water could not penetrate more than a few feet of soil.

Obviously, the vessel must have been located beneath an impermeable stratum, a most unfortunate circumstance.[32]

The third pioneer, the astronomer Edmond Halley, proved by his calculations that water evaporated from the oceans and came down as rainfall in ample amounts to sustain the flows of rivers. Thus, between the three scientists, the concept of the hydrologic cycle became firmly established even though many noted investigators later refused to believe it. They were the first hydrological investigators to use quantitative results to prove their hypotheses, and that is undoubtedly their greatest contribution to hydrology.

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