EDMOND HALLEY, F.R.S., HYDROLOGIST EXTRAORDINARY

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Introduction

EDMOND HALLEY (1656–1742) was a versatile genius, primarily known as a pioneer in astronomy, geophysics and mathematics. He was also interested in history, navigation, archaeology and civil engineering. He wrote poems in Latin and translated ancient works on geometry from Greek and Arabic texts. He was the founder of population and actuarial statistics, and, in my opinion, he was one of the co-founders of experimental hydrology.

It is surprising to note that Halley's substantial contributions to hydrology have received such scant attention while his manifold contributions to other disciplines have been well documented and thoroughly discussed. Before the writer's work, only two other authors conducted serious studies on the development of the science of hydrology and both of them, Adams (1, 2) and Meinzer (3, 4), just barely mention Halley's work. This is difficult to understand, when one considers that it was Halley who for the first time presented the experimental solution to a major problem associated with the concept of the hydrologic cycle, a most fundamental concept of hydrology.

The chronology of the experimental development of the concept of the hydrologic cycle is as follows:

1674—Pierre Perrault (1608–1680), the French naturalist, proved in 1674 that rainfall was more than adequate to sustain river flows (5).

1686—Edmé Mariotte (1620–1684), the French physicist, confirmed Perrault's findings. Mariotte's investigations were more precise than those of his predecessor (6).

1687—Edmond Halley proved that the amount of water which evaporated from the oceans and watercourses and which came down in the form of rainfall adequately replenished the flow of the rivers (7).

Thus, it is obvious that Halley's contribution to the development of hydrology was substantial, and he should, as I have suggested (8, 9, 10, 11, 12), be considered to be a co-founder of experimental hydrology along with Pierre Perrault and Edmé Mariotte.

WATER BALANCE OF THE MEDITERRANEAN SYSTEM

Halley's interest in evaporation may well have been aroused when he was on the island of St Helena, in 1677–1678, to make observations of southern stars which could not be observed from Europe. His celestial observations there were generally taken at night at an altitude of between 2000 and 3000 feet (13). 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 glasses every few minutes to keep them clear. He also had trouble in recording his observations because the paper became too wet to accept ink. It is equally possible that his work on evaporation may well have been suggested by the experiments of Perrault and Mariotte. Halley was certainly aware of their works, at least through the extensive reviews that appeared in the *Philosophical Transactions* in 1675 and 1686 respectively (14, 15). Be that as it may, on his return from St Helena, Halley demonstrated that evaporation from the oceans is more than is needed to replenish all springs and rivers (7, 16).

Halley's experiments on evaporation were conducted at Gresham College in London, which was also the early meeting place of the Fellows of the Royal Society (17). The results of his investigation were reported in four papers published in the *Philosophical Transactions* in 1687, 1691, 1694 and 1715 respectively.

In order to estimate the amount of water evaporating from the Mediterranean, Halley took a pan of salt water, 4 inches deep and 7.9 inches in diameter, and attached it to one end of the beam of a balance having counterpoising weights on the other side. The water was maintained at a temperature equal to that of 'our hottest summer' by the occasional application of coal fire. It was found, at the end of 2 hours, that 233 grains of water had evaporated. The unit of weight used by the astronomer was pound troy, which is currently obsolete. (The relationships between pound troy and pound avoirdupois is as follows: 1 ounce troy = 480 grains = 1.09714 ounces avoirdupois; 12 ounces = 1 pound troy = 0.82286 pound avoirdupois.)

Thus, the depth of water evaporating from the pan in two hours amounted to:

$$\frac{223 \times 76}{1726} \times \frac{1}{49} = \frac{1}{53} \text{ inches}$$

He assumed, for the above computation (on the basis of an experiment made in the Oxford Society by Dr Edward Bernard), that 1 cubic foot of water weighed 76 pounds troy. The rate of evaporation, however, for simplifying subsequent calculations, was taken as 1/120 inch per hour. Halley suggested that it would be logical to assume that evaporation took place at the above rate only for 12 hours per day, during the period the Sun was up, because:

> the Dews return in the Night, as much if not more, Vapours than are then emitted; and in summer the Days being longer than twelve hours, this excess is ballanced by the weaker Action of the Sun, especially when rising before the Water be warmed. . . . (7)

Under these assumptions, said Halley, water would evaporate at the rate of 6914 tons per day per square mile of surface area.

If the Mediterranean Sea is estimated to be 40 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 5280000000 tons. He went on to say, quite correctly, that the figure arrived at was rather conservative, because evaporation depends to a great extent on wind—and its effect was completely neglected in his calculations.

In order to calculate the amount of water the Mediterranean received from the rivers that enter into it, Halley considered only the nine major ones—Iberus, Rhone, Tiber, Po, Danube, Neister, Borysthenes, Tanais, and Nile and suggested that if their flows were overestimated, it would compensate the exclusion of 'all the small rivulets that fall into the Sea, which otherwise I know not how to allow for'. Halley further assumed that each of the nine rivers had a discharge equal to ten times that of the Thames at Kingston Bridge. Since the cross-sectional area of the Thames there was 300 × 9 feet, and its velocity was 2 miles per hour, the total flow per day was 20300000 tons. Hence, the total amount of fresh water received by the Mediterranean per day was 20.3 × 10 × 9 = 1827 million tons.

Thus, according to Halley's calculations, the Mediterranean Sea lost 5280 million tons of water per day due to evaporation while it received only 1827 million tons of water from the rivers that enter into it. Since the gain was slightly more than one-third the total loss of water, it appeared to demonstrate the fact that enough water evaporated to continuously supply all the contributing streams and rivers although, of course, the inflow through the Straits of Gibraltar was not taken into account.

Circulation of vapours and cause of springs

In a second paper, published in 1691, Halley 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 decreased by the loss in Vapour;

nor yet abounded by the immense quantity of fresh water it receives continually from the Rivers (18).

He started with an explanation for the evaporation process. 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. This, suggested Halley, might not be the only mechanism involved as there could be 'a certain sort of matter whose *conatus* may be contrary to that of Gravity: as is evident in Vegetation . . .'. Be that as it may, the fact remains that heat did raise vapour, and with an increase of heat, more and more particles of water were separated and emitted with a greater velocity, as could be seen in case of boiling cauldrons. Since the Sun heats the air during the day, it raises 'more plentiful vapours from the water'. Warm air is capable of holding more aqueous vapour, and hence during the night, when it becomes gradually cooler, some of the vapour is discharged as dew. The process was somewhat analogous to the fact that more salt can be dissolved in warm water than in cold water; but as the temperature of the solution comes down, some of the dissolved salt is precipitated.

Halley then suggested:

> Let us suppose this Ocean [between the tropics] interspersed with wide and spacious Tracks of Land, with high ridges of Mountains . . . on the tops of which the Air is so cold and rarefied as to retain but a small part of those Vapours that shall be brought Hither by the Winds. 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 Hither runs over by the lowest place, and breaking out by the sides of the Hills, form single *Springs* (18).

The springs unite to form small rivulets which in turn unite to form rivers. The theory, asserted Halley, was not a 'bare Hypothesis' but founded on his 'Experience' at St Helena.

There was a fundamental difference between Halley's concept on the origin of springs and that of Perrault and Mariotte. Both Perrault and Mariotte contended that rivers originate from rainfall, and proved experimentally that rainfall was more than adequate to sustain river flows. Halley, on the other hand, favoured neither the pluvial nor the percolation concept. (The percolation concept was put forward in the Middle Ages, and was quite prevalent till about the eighteenth century. According to it, water at the sea bed passed through hidden channels to the earth, and then ascended to the land surfaces or to the mountain tops. The channels eventually became so minute that only fresh water could pass through, and all the salt was left behind.) As to the pluvial theory, Halley contended that it could not be correct since rainfall is intermittent whereas many of the springs are perpetual and 'without diminution, even when no Rain falls for a long Space of Time', and the greatest rivers have their most copious sources farthest from the sea.

Halley believed, as would be obvious from the last quoted passage, 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'. He concluded:

> This, if we may allow final Causes, seems to be the design of the Hills, that their Ridges being placed through the midst of Continents, might serve, as it were for Alembicks to distil fresh Water for the use of Man and Beast, and their heights to give a descent to those Streams to run gently, like so many Veins of the *Macrocosm*, to be the more beneficial to the Creation (18).

Even though Halley's condensation hypothesis was not correct, he did have a reasonably clear conception of the hydrologic cycle. He explained it as follows:

> 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 Winds 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 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, after the Earth is fully sated with moisture, does by the Valleys or lower Parts of the Earth find its way into the Rivers. After this manner is the Circulation performed. . . . (18).

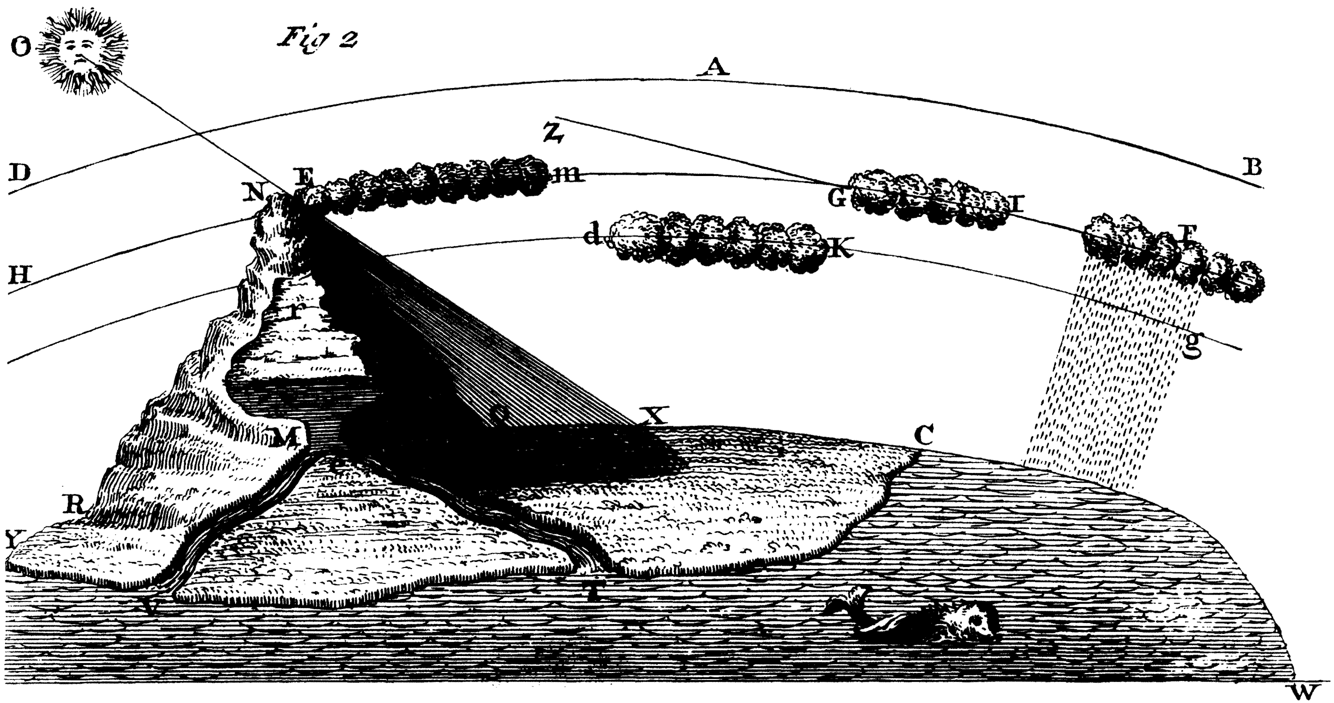

FIGURE 1. Halley's concept of the hydrologic cycle

Figure 1 is a charming illustration of Halley's concept of the hydrologic cycle from an early eighteenth century book (19) on hydraulics (probably the first English work bearing the title 'hydraulics'—a term introduced by Robert Boyle). Switzer, the author of that book, disagreed completely with Halley's, Perrault's and Mariotte's concepts, however. He favoured the capillary theory of springs.

The 1691 paper concluded with a speculation about the differences between rain and dew. When two contrary winds meet, and the barometric pressure is high, air is heated up, and, consequently, vapour is better sustained and prevented from coagulating into drops. Under these conditions, clouds are not easily generated, and at night, vapour descends 'single as they arose in imperceptible Atoms of Water'. However, when the two contrary winds diverge, and the barometric pressure is low, the air becomes rarefied and cannot prevent the vapour from coalescing into rain drops. 'To which', he added, ' 'tis possible and not improbable, that some sort of Saline or Angular Particles of Terrestrial Vapour being immixt with the Aqueous, which I take to be Bubbles, may cut or break their Skins or Coats, and so contribute to their speedy Condensation into Rain.'

Measurements of evaporation

In his third paper, published in 1694 (2), Halley reported the results of the investigation carried out in Gresham College under his direction 'with great care and accuracy', by Henry Hunt, the 'Operator' to the Royal Society, in 1693. The evaporation from a screened and sheltered water surface, having a surface area of 8 square inches, was noted every day for the year 1693. Also recorded were temperature, pressure and general precipitation conditions (snow, rain or frost). All observations were taken at 8 a.m. The total annual evaporation turned out to be 64 cubic inches, or 8 inches of water per square inch of the surface area. He compared it with Perrault's recording of 19 inches of annual rainfall in Paris (21) and Townley's 40 inches at the foot of the hills in Lancashire (21), but evidently the water evaporated was insufficient to account for the total annual precipitation. His explanation for the shortage of evaporation required to balance the rainfall, was that the direct effects of the Sun and the wind had been excluded in his experiment. He estimated that the wind effect would have increased the evaporation by at least three times, and the Sun effect 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 of March, April, September and October. Halley, however, does not state anything about the container of water from which evaporation took place. It was probably a 'pan of water'—like the one used for his previous evaporation experiment, filled to the top every morning at 8 o'clock.

The rate of evaporation, observed Halley, is reduced by a layer of vapour which seemed to 'adhere' to the water surface. He suggested that this causes refraction of light which makes the heights of objects on the shore appear exaggerated when viewed from the sea. It also accounts for cattle being visible from Greenwich on the Isle of Dogs during high tide but not during low tide.

His fourth and the final paper of the group (22) was published in 1715. It is of considerable interest to all historians of science and technology. Halley considered four closed-in (i.e., having no exit) seas and lakes: Caspian Sea, Dead Sea, Lake of Mexico and Lake Titicaca. He noted that the lakes and seas under consideration have no outlets even though they received water continuously from various rivers, and he reasoned that the levels will rise 'until such time as their surfaces are sufficiently extended, so as to exhale in vapour that water that is poured in by the river'. He also noted that rivers are continually carrying dissolved salt to the ocean, and suggested that since the loss through evaporation is only of fresh water, the salinity of the sea must be steadily increasing. Thus, if the quantity of salt present in a certain volume of water is determined at a fixed place in the dryest weather, and similar measurements are taken in the same place under similar conditions 'after some Centurys of Years', then from the increase in the degree of salinity, it should be possible to estimate the age of the Earth. Halley recommended to the Society that experiments should be conducted to determine the salinity of the ocean and 'as many of these Lakes as can be come at' for the benefit of the future generations.

It should be noted that it was commonly believed during the seventeenth and the early eighteenth centuries that the salinity of the sea was due to the presence of rocks containing salt in its bed, and the rivers flowing into the sea reduced its salinity by their fresh water. He said:

> If it be objected that the Water of the *Ocean*, and perhaps of some of these *Lakes*, might at the first Beginning of Things, in some measure contain Salt, so as to disturb the Proportionality of the Encrease of Saltness in them, I will not dispute it: But shall observe that such a Supposition would be so much contract the Age of the World, within the Date to be derived from the foregoing Arguement, which is chiefly intended to refute the ancient Notion, some have of late entertained, of the Eternity of all Things; though

perhaps by it the World may be found much older than many have hitherto imagined.

In 1898, John Joly had enough data available to estimate the age of the Earth along the lines suggested by Halley. Joly's calculations showed that 80 to 90 million years will account for all the salt now dissolved in sea water. This is in sharp contradiction to the radiometric estimate of the age of the Earth of about 4500 million years. There are two main reasons for such a discrepency. The theory erroneously assumes that (i) the rate at which rivers transfer salts to the ocean has remained constant over the geological time, and (ii) salts having found their way to the ocean remain there for all times. Holmes (23) in a recent study accounted for some of the errors committed by Joly, and came out with an estimate of 250 million years which, he correctly pointed out, is a rough estimate of the average time spent in sea water by a sodium ion.

Halley also considered the 'Noachian Deluge' in a paper read before the Royal Society towards the end of 1694. The paper, however, was published in 1724 because the author feared that 'by some unguarded Expression he might incur the Censure of the Sacred Order' (24). Thus, Halley's work precedes that of William Whiston who expressed somewhat similar views in *New Theory of the Earth*, published in 1696. The 'Noachian Deluge' was quite a popular subject for discussion by naturalists during the late seventeenth and early eighteenth centuries. Since it has a considerable bearing on the development of scientific geology as well as hydrogeology, and because many members of the Royal Society took part in the discussions, it would be a suitable subject for a future paper.

Conclusions

It is quite clear from the above discussion that Edmond Halley made a substantial contribution to the development of the science of quantitative hydrology, but what is not clear is the reason why Halley has not received the just credit he deserves—especially in hydrologic literature. Admittedly, Halley was not entirely correct in his explanation of the origin of springs and rivers, but the reason for this is not difficult to discover. While at St Helena, Halley's experiences consisted largely of meeting an uncivil Governor, enduring unfavourable weather, and observing heavy condensations of vapour on the mountain. Obviously, the last factor made such an impression on young Halley (who was scarcely 21 at that time) that he considered it to be the true origin of the water flowing in streams.

We must nevertheless realize that Halley's investigations proved quite categorically a very fundamental aspect of the concept of the hydrologic cycle, namely that enough water evaporated from the oceans to sustain river flows. This, by itself, is a major contribution and its effect on the development of experimental hydrology is indeed incalculable. Between the three scientists, Pierre Perrault, Edmé Mariotte and Edmond Halley, the concept of the hydrologic cycle was experimentally established for the first time. In all fairness, therefore, all the three should be given credit for being the co-founders of scientific hydrology.

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