The nature of the hydrologic cycle is one of the oldest and most important questions in geology (Deming 2005, 2014, 2018). The mystery was how the water balance between oceanic, terrestrial, and atmospheric waters was maintained. As Edmond Halley (Figure 1) himself noted, over the course of recorded human history “the sea has not sensibly decreased by the loss in vapor; nor yet abounded by the immense quantity of fresh water it receives continually from the rivers” (Halley 1691, 469). There had to be some return flow of sea water to the land, but how this occurred was debated for hundreds of years.

The first person to unequivocally assert that all stream flow was sourced in precipitation and infiltration was the potter, Bernard Palissy (c. 1510–1590). In his book, Admirable Discourses, Palissy concluded that “all fountains proceed only from springs produced by rain” (Palissy 1957, 55). But Palissy’s arguments were not widely accepted. Systematic and quantitative hydrologic studies were not conducted until the latter decades of the 17th century.

In De l’origine des fontaines (1674) Pierre Perrault (1611–1680) published the first quantitative estimates of precipitation in a drainage basin and showed it was sufficient to account for all stream flow (Perrault 1674). However, Perrault did not fully understand the process of infiltration. Perrault’s experiment was repeated and refined by his colleague in the French Academy of Sciences, Edme Mariotte (c. 1620–1684). In Traité du mouvement des eaux et des autres corps fluides, Mariotte (1686) conceded that infiltration was not universal and uniform, but anticipated the modern theory of macropores by arguing “that in uncultivated land, and in woods, there are several little canals, which are very near the surface of the earth, into which the rainwater enters; and that those canals are continued to a great depth” (Mariotte 1718, 16–17).

It is certain that the work of Perrault and Mariotte was read and contemplated by members of the Royal Society in England (Dooge 1974). Both Perrault’s De l’origine des fontaines (1674) and Mariotte’s Traité du mouvement des eaux et des autres corps fluides (1686) were reviewed in the Royal Society’s Philosophical Transactions almost immediately following their publication. Among the Fellows of the Royal Society interested in hydrological problems was Edmond Halley (1656–1743). “The magic of numbers has earned for Pierre Perrault, Edme Mariotte, and Edmond Halley the title of founding fathers of the science of hydrology” (Parizek 1963, 4).

Halley the Polymath

Edmond Halley was a man of such prodigious and varied accomplishments that his biography is difficult to write (Figure 2). “His output of papers was phenomenal, his unpublished work prodigious, and his range of interests surprising even for the seventeenth century” (Ronan 1969, 140). Halley was born on October 29, 1656, while the Scientific Revolution was still in progress. His birth date is certain, as John Aubrey (1626–1697) informs us that he obtained the date “from Mr. Halley himself” (Aubrey 1898, 282). Halley’s father was a soapmaker with no intellectual pedigree, but an industrious individual who had become prosperous through frugality and prudent investments. The father determined that his son should have a first-class education and the youth was initially schooled at home by a hired tutor. When Edmond was old enough he was enrolled at St. Paul’s school, an eminent private school for boys established in AD 1509. At St. Paul’s, it was said that Halley “excelled in every branch of classical learning, but was particularly taken notice of for the extraordinary advances he made at the same time in mathematics” (Anonymous 1757, 2494). Although this assertion may strike the reader as hagiographical, it is entirely consistent with Halley’s later achievements.

At age 17 Halley entered Queen’s College at Oxford. At Oxford Halley studied Latin, Greek, and Hebrew, and
acquired “so much knowledge in geometry as to make a complete dial” (Wood 1820, 536). But Halley’s chief preoccupation was astronomy. He brought to Oxford an extraordinary collection of astronomical instruments that had been purchased by his father “who spared no expense to encourage his son’s genius” (Anonymous 1757, 2494). These were no amateur instruments. Halley had a telescope some 24 feet in length and a sextant 2 feet in diameter (Ronan 1969, 8). In Catalogus Stellarum Australium, Halley (1679) recorded that his youthful study of astronomy “was so intense that I read through and found out in a short time every hidden fact in that science” (Ronan 1969, 7).

In time, Halley’s interests expanded beyond astronomy to encompass an enormous range of subjects (Biswas 1970). These included meteorology, geophysics, mathematics, oceanography, and hydrology. Nor was his research and writing limited to the sciences. Halley published a paper on the history of the city of Palmyra (Halley 1695) and attempted to reconstruct the time and place at which Julius Caesar first landed in Britain (Halley 1686). Halley (1693) also authored a short paper that became the foundation of the science of social statistics and the basis of the life insurance business, An Estimate of the Degrees of Mortality of Mankind.

Experiments Concerning Evaporation

Halley’s thoughts and experiments on the hydrologic cycle were published in two issues of the Transactions of the Royal Society in 1687 and 1691 (Halley 1687, 1691). Publication dates for these manuscripts are uncertain. It is difficult to ascertain exact dates for composition and publication of Transactions manuscripts for the latter half of the 1680s. These were years of political tumult and social unrest in Britain that culminated in the Glorious Revolution of 1688 (Deming 2012, 243–247). Manuscripts were evidently collected for some time and published in a numbered issue of the Transactions. A number of issues were then bound together in a volume with an assigned date that could differ by a few years from the actual date of publication.

Halley’s first hydrological paper, An Estimate of the Quantity of Vapour Raised Out of the Sea by the Warmth of the Sun, described an experiment designed to estimate the magnitude of water evaporated from the Earth’s oceans. As Halley explained, “in what proportion these vapours [water] rise, which are the sources not only of rains, but also of springs and fountains has not, that I know of, been well examined” (Halley 1687, 366).

Halley placed a thermometer in a pan of water and heated it by holding it over a bed of coals. We are not informed of the temperature reached or maintained. Halley only stated “we brought the water to the same degree of heat which is observed to be that of the air in our hottest summers” (Halley 1687, 367). Weighing the pan before and after evaporation, Halley found that water “exhales the thickness of 60 parts of an inch in two hours from its whole surface . . . which quantity, will be found abundantly sufficient to serve for all the rains, springs and dews” (Halley 1687, 367–368). This estimate had to be regarded as a minimum because evaporation could also be caused by “the winds, whereby the surface of the water is licked up sometimes faster than it exhales by the heat of the sun” (Halley 1687, 368).

Halley proceeded to apply the results of his experiment to explain why flow from the Atlantic Ocean to the Mediterranean Sea through the Straights of Gibraltar was always influent. Extrapolating from his crude experiment with the pan of water warmed by burning coals, Halley estimated the amount of water vapor evaporated from the surface of the Mediterranean Sea on a summer day to be 5280 million tons (Halley 1687, 368).

To estimate river flow into the Mediterranean, Halley began by working with a convenient stream that he could measure directly: the Thames River. Halley estimated flow through the Thames at the Kingston Bridge, the first sensible point above tidal influences, by multiplying the flow rate by the cross-sectional area of the river basin. This was a crude method, because even at that time it was known that the flow rate in a river was not constant but varied throughout the basin. In Traité du mouvement des eaux et des autres corps fluides, Edme Mariotte (1686) noted that flow near the base and sides of a stream is not so fast as the middle surface (Deming 2018).

Halley estimated flow through the Thames to be about 19 million m³ per day, about three times the modern estimate. He then assumed that nine major rivers flowing into the Mediterranean each contributed 10 times the flow of the Thames in England. Why 10 times as much?
Because, Halley explained, “not that any of them is so great in reality, but to comprehend with them all the small rivulets that fall into the sea, which otherwise I know not how to allow for” (Halley 1687, 369).

Halley concluded that cumulative river flow into the Mediterranean Sea was “little more than one-third of what is proved to be raised in vapour out of the Mediterranean in 12 hours time” (Halley 1687, 369). Thus the Mediterranean necessarily had to be constantly recharged by an influx from the Atlantic Ocean. Although Halley’s estimates and methods were crude by modern standards, his approach was quantitative and experimental, a contrast to the unbridled sort of theoretical speculations that often characterized the natural philosophy of the preceding centuries.

The Cause of Springs

In Halley’s (1691) second hydrological paper, *An Account of the Circulation of the Watry Vapours of the Sea, and of the Cause of Springs*, he attempted to complete his description of the hydrologic cycle by explaining the fate of water evaporated from the ocean.

According to the ancient Greek theory of the four elements, the evaporation of water was regarded as the transformation of the element of water into the element of air. The ancients had no way of discerning that air was not a homogeneous substance. In the latter half of the 17th century, the science of chemistry was still in a nascent state of development (Deming 2016). But it is apparent from Halley’s conclusions that he and others had moved beyond the ancient Greek theory of four elements and recognized that air could be a heterogeneous mixture of different gasses. Halley had adopted the atomic theory and he regarded water vapor as a substance distinct from air.

After being heated, Halley (1691) postulated that atoms of water expanded and were “dispersed into and assimilated with the ambient air” (p. 469). Water vapors were then carried by wind into the interiors of the continents where they were “compelled by the stream of the air to mount up with it to the tops of the mountains, where the water presently precipitates” (Halley 1691, 471). Precipitation occurred because “the air is so cold and rarified [on mountain tops] as to retain but a small part of those vapours” (Halley 1691, 470–471).

Halley sidestepped the difficult question of how infiltration occurred, and whether or not it was universal and uniform. Instead he postulated that water would gather in “caverns of the hills,” reminiscent of Aristotle’s conception of air turning into water inside caves (Halley 1691, 471). “Breaking out by the sides of the hills,” the water thus collected “forms single springs” (Halley 1691, 471). These in turn combined to form “little rivulets or brooks,” and the smaller streams merged in a common valley to “become a river” (Halley 1691, 471).

It was not obvious that this process would supply enough water to maintain flow in a major river. Addressing this difficulty, Halley argued that “one would hardly think the collection of water condensed out of vapor [to be sufficient], unless we consider how vast a trace of ground that river drains” (Halley 1691, 471). He then proposed “a rule, that the magnitude of a river... is proportionable to the length and height of the ridges from whence its fountains arise” (Halley 1691, 471).

In this age of experimental philosophy, the savants of the Royal Society were anxious to distinguish their work from the idle speculations of natural philosophers. Isaac Newton used the word *hypothesis* to describe the unconstrained speculations that had characterized the natural philosophy of the past (Deming 2012, 224). Newton contrasted *hypothesis* with *theory*. For Newton, a *theory* was an explanation derived directly from observation or experimentation. Halley thus considered it essential to point out that “this theory of springs is
not a bare hypothesis but founded upon experience” (Halley 1691, 471). The experience Halley referred to was his trip to the island of St. Helena. In 1676 Halley, then a youth of 20, made his first significant scientific contribution by mapping the stars of the southern hemisphere. On St. Helena, Halley found that his observations were continually hampered by condensation at high altitudes (Cook 1998, 73). This condensation, Halley noted, “was a great impediment to my celestial observations” (Halley 1691, 471).

Halley recognized the role of terrestrial precipitation in the hydrologic cycle, but evidently believed that most contributions to stream flow occurred through overland flow. He doubted that infiltration and groundwater flow was sufficient to maintain the discharge from natural springs for long periods of time. Halley concluded that his hypothesis of condensation at high altitudes “is more reasonable than that of those who derive all springs from the rain-waters” (Halley 1691, 472). He argued that it was often the case that “no rain falls for a long space of time,” yet some springs “are perpetual and without diminution” (Halley 1691, 472).

Estimating the Age of the Earth

Among Halley’s other scientific contributions was a proposal to use what might be called a hydrological methodology to estimate the age of the Earth from the salt content of the ocean. Halley was the first person to propose this method. In a discussion published in the Royal Society’s Philosophical Transactions in 1714, Halley first acknowledged that Christian and Jewish scriptures had confined human history to 6000 or 7000 years. But he argued against a literal interpretation of the days of creation described in Genesis. “Nor can it be well conceived how those days should be to be understood of natural days, since they are mentioned as measures of time before the creation of the Sun” (Halley 1714, 196).

Halley then described a novel method for estimating the age of the Earth. He noted that the saltiness of lakes without drainage increased through time. The streams that fed them carried in dissolved solids that never left. The oceans of the world were analogous. They received an influx of salt from all the world’s rivers. Unlike water, salt never left the oceans. Halley argued that if measurements of the ocean’s salt concentration could be made at different points in time the rate of increase could be estimated and extrapolated back to time zero, the beginning of the Earth. It was “an argument for estimating the duration of all things, from an observation of the increment of saltiness in their waters” (Halley 1714, 298). Halley conceded that the rate of salt increase in the ocean was probably too slow to be detectable in a human time frame. He concluded that his method “can be of no use to ourselves, it requiring very great intervals of time to come to our conclusion” (Halley 1714, 299).

Toward the end of the 19th century, Halley’s method for estimating the age of the Earth was implemented by the Irish physicist, John Joly (1857–1933). Instead of comparing measurements of the ocean’s saltiness at different times, Joly estimated the rate at which the salt content was increasing by measuring the rate at which salt was being carried to the ocean by the world’s major rivers. He concluded that “a period of between eighty and ninety millions of years had elapsed since water condensed upon the Earth” (Joly 1898, 64). From radioactive dating, we know that Joly’s estimate was far too short. The modern estimate of the age of the Earth is 4.5 billion years (Dalrymple 1991, 1). Joly’s estimate was in error because the residence time of salt in the oceans is not infinite. Salt is physically removed from the oceans by precipitation and deposition of halite, as well as physical processes in the plate tectonic cycle. The nature of these processes would have been unknown in either Joly’s or Halley’s time.

Contributions to Other Sciences

Halley’s range of interests and contributions to the sciences were wide ranging and significant. He was most noted as an astronomer. When he returned from St. Helena in 1678, King Charles II directed Oxford University to award Halley the degree of master of arts, and he was elected a Fellow of the Royal Society. The publication of Catalogus Stellarum Australium (1679) cemented Halley’s status as an astronomer and scientist of the first rank.

Halley was most renowned for his work on comets. Indeed, Halley’s expertise in the subject was acknowledged by no less an authority than Isaac Newton. Much of the discussion of comets in Principia gives credit to Halley. In 1705, Halley published (in Latin) what was perhaps his most important work in astronomy, Astronomiae cometicae synopsis (Halley 1705a). The work was translated into English and published the same year as A Synopsis of the Astronomy of Comets. Halley’s Synopsis begins with a short history of comets, from Aristotle through the work of Isaac Newton. The heart of this concise work is a table showing “the astronomical elements of the motions in a parabolic orbit of all the comets that have been hitherto duly observed” (Halley 1705b, 7). This short table listing the elements of 24 cometary orbits was, in Halley’s words, “the result of a prodigious deal of calculation” (Halley 1705b, 6). Halley explained, “I have considered the orbits of comets as exactly parabolic... they move in very eccentric orbits and make their returns after long periods of time” (Halley 1705b, 20).

Halley’s immortality was assured by what was almost an innocuous afterthought in Synopsis. Halley ventured the opinion that the comets of 1531, 1607, and 1682 were nothing more than the periodic reappearance of the same body. “There are many things which make me believe that the comet which Apian observed in the year 1531 was the same with that which Kepler and Longomontanus took notice of and described in the year 1607 and which I myself have seen return and observed in the year 1682” (Halley 1705b, 21). Halley then predicted the comet’s future return. “Hence I dare venture to foretell that it
will return again in the year 1758” (Halley 1705b, 22). Although superficially Halley’s prediction appears to be trivial, it was the offspring of an “exceedingly difficult” calculation because Halley had to account for gravitational perturbations in the comet’s path caused by Jupiter and Saturn (Ronan 1969, 149). Halley’s forecast was the “first successful prediction of a cometary return” (Newburn and Yeomans 1982, 298). It was also a corroboration of Newton’s law of universal gravitation, and a validation of the law’s usefulness and accuracy in calculating celestial motions.

Halley may justly be called the founder of the science of geophysics. He theorized on the origin of the Earth’s magnetic field (Halley 1683), and made two voyages through the north and south Atlantic Oceans to map variations in the Earth’s magnetic field. In 1701, Halley published the results of his magnetic studies in the form of a map showing the variations in magnetic declination throughout the North and South Atlantic Oceans, A New and Correct Chart Shewing the Variations of the Compass in the Western and Southern Oceans (MacPike 1937, 275). Halley’s map was the first presentation of isogonic lines, an isogon being a line connecting points of equal magnetic declination. Halley’s isogonic map has been ranked as “one of the most important charts in the history of cartography” (Cook 1998, 283).

A formidable mathematician, Halley also published translations of works by the Greek mathematician Apollonius who lived and worked during the third century BC. These included Conics, De Sectione Rationis (On the Cutting-off of a Ratio) and De Sectione Spatii (The Cutting-off of an Area), De Sectione Rationis existed only in Arabic, and Halley knew no Arabic. Halley sat down and accomplished the translation by essentially teaching himself Arabic word-by-word.

**Persistence of the Sea Percolation Theory**

Despite the substantive arguments and measurements made by Perrault, Mariotte, Halley, and others, the old idea that the hydrologic cycle was maintained by circulation through the solid earth from the sea to the land lingered for some time. Among those who endorsed the idea was William Derham (1657–1735), natural theologian and Fellow of the Royal Society. Derham’s Physico-Theology, first published in 1713, invoked the Design Argument (Deming 2008) to argue that the features of the Earth were beautifully and purposefully designed by God. Among those influenced by Physico-Theology was William Paley (1802), whose book Natural Theology marked the culmination of two centuries of British natural theology (Knight 2008).

Derham believed that terrestrial waters were sourced in the sea because some springs flowed perennially at the same rate, exhibiting no perceptible correlation with variations in precipitation. “That springs have their origin from the sea, and not from rains and vapors, among many other strong reasons, I conclude from the perennity of diverse springs, which always afford the same quantity of water” (Derham 1720, 51). Derham cited the example of a perennial spring known to him in the parish of Upminster, which seemed to have insufficient topography to provide groundwater flow to the spring. The lands immediately surrounding the spring were, Derham noted, “about 15 or 20 feet higher than the spring; and the lands above that, of no very remarkable height” (Derham 1720, 51). To explain uphill flow from the sea to the land, Derham invoked capillary forces. The difficult question of how salt water became fresh was ignored.

The sea-to-land percolation theory was also adopted by the gardener Stephen Switzer (1682–1745). In An Introduction to a General System of Hydrostaticks and Hydraulicks, Switzer (1729) described the work of both Mariotte and Halley in some detail, yet rejected their conclusions (Figure 3). Switzer invoked the ancient doctrine of the Microcosm and the Macrocosm, arguing by analogy that “water serves the Earth for the same purposes, as the blood does the body, or the sap the trunk and boughs of a tree” (Switzer 1729, 16).

Sea water, Switzer concluded, traveled “through all the permeable parts and subterraneous channels of the Earth, in a due circulation and ascent… through those veins, channels, and ducts of the Earth, till it breaks out of the sides of the hills, and traverses its way, even to its return into the sea again” (Switzer 1729, 16).

Switzer conceded that although Halley’s theory of condensation at high altitudes might be plausible in some locations, it would not work in England. “Common experience tells us, that in England, at least, there is no such thing” (Switzer 1729, 21). Switzer also made logical objections to Mariotte’s claim that all stream flow originated in precipitation. “If rains be the occasion of springs, how comes it to pass, that some very large tracts of lands, such as we have in the west of England, have but few… whilst others more northward, abound in very large rivers” (Switzer 1729, 24). The existence of mineral and hot springs was also invoked by Switzer as evidence tending to falsify the theory precipitation and infiltration. “Tell us, how it comes to pass, that one spring is so hot, another so bitter, and a third so salt… can they proceed from rain or any other superficial cause?” (Switzer 1729, 31).

The persistence of the sea-to-land theory of recharge illustrates how intelligent men can make reasoned arguments buttressed by substantive empirical evidence that ultimately prove to be completely wrong. The history of science is a history of error and a testament to the limitations of human reason.

**From Natural Philosophy to Science**

Upon perusing Halley’s (1691) paper on the cause of springs, the modern reader may be startled to read the assertion that there may exist “a certain sort of matter whose conatus may be contrary to that of gravity” (469). A conatus is “a force, impulse, or tendency simulating a human effort” (Oxford English Dictionary 1913, 752). It is an ancient term in natural philosophy, reminiscent
of Aristotle’s concept of natural motion. In *De Caelo*, Aristotle (1953) explained that “simple bodies... contain a principle of natural motion, like fire and earth” (11–13). Thus fire moved upward, while objects containing the element of earth tended to move downward.

Halley borrowed other concepts from two thousand years of natural philosophy. He invoked final causes and the ancient doctrine of the macrocosm and the microcosm. He speculated that “if we may allow final causes,” the design of the hills... their ridges being placed through the midst of the continents, might serve as it were for alembicks to distill fresh water for the use of man and beast” (Halley 1691, 473). An *alembic* was an apparatus used by alchemists and early chemists for distillation. Thus the streams maintained by condensation on mountain ridges were “like so many veins of the macrocosm, to be the more beneficial to the creation” (Halley 1691, 473).

Halley’s discourse is a reminder that even at the very height of the Scientific Revolution, the most brilliant men stood with one foot in the Middle Ages. They struggled with concepts that today we find to be elementary, such as the physics of motion. Herbert Butterfield (1900–1979) noted that “things which would strike us as the ordinary way of looking at the universe... defeated the greatest intellects for centuries... of all the intellectual hurdles which the human mind has confronted and overcome in the last fifteen hundred years, the one which seems to me to have been the most amazing in character and the most stupendous in the scope of its consequences is the one relating to the problem of motion” (Butterfield 1965, 14–15).

The conclusive breakthrough to the modern age was the publication of Isaac Newton’s (1687) *Principia*. In one fell swoop, Newton single-handedly transformed physics from a natural philosophy concerned with speculation, logical argumentation, and final causes, to an exact mathematical science based on empiricism. It is hardly possible to exaggerate the importance of Newton’s achievement. Newton’s contemporaries regarded his physics as divinely inspired. Thus the words of the poet, Alexander Pope (1824, 378):

\begin{quote}
Nature and nature’s laws lay hid in night:
God said, let Newton be! and all was light.
\end{quote}

And it was Edmond Halley who was instrumental in motivating Newton to write and publish *Principia*. Upon visiting Newton at Cambridge in August of 1684, Halley was astonished to discover that Newton had solved the greatest problem in the history of science, explaining the motion of the planets in the Solar System. Newton had succeeded in demonstrating mathematically how an inverse square law of gravitation led directly to Kepler’s three laws of motion (Deming 2012, 236). Encouraged by Halley, Newton worked tirelessly for 18 months. When the manuscript was complete, Halley discovered to his horror that the Royal Society had no funds to pay for its publication. So Halley undertook the expense of publication out of his own pocket. Were it not for Halley’s friendship and dedication, humanity might have lost the greatest scientific contribution.

Thomas Carlyle (1795–1881) proposed that “the history of what man has accomplished in this world, is at bottom the history of the great men who have worked here” (Carlyle 1840, 3). Although the “Great Man Theory” has fallen out of fashion, a perusal of the achievements of men like Halley and Newton make it difficult to discount.

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