14 AFTERWORD – A SHORT HISTORICAL SKETCH OF THEORIES ABOUT THE WATER CIRCULATION ON EARTH

14.1 EARLIEST CONCEPTS: THE ATMOSPHERIC WATER CYCLE

For as long as humans have been on Earth, they must have been acutely aware of their dependency on different forms of water in their environment. Water was literally vital for their health and sustenance but it could also be destructive and even lethal in severe weather, floods, and the other hazards they faced in their daily lives. Already in the earliest writings there are indications that among natural peoples in their primal stage it was a common notion that water in nature moves continually between different states in some repetitive, if not cyclical, fashion. Whatever is left of these early writings is not always easy to interpret, mainly because the meanings of even the most elementary concepts have evolved in the meantime. Nor is it always easy to distinguish profane views and naturalistic descriptions from the more sacred narratives and religious interpretations. Nevertheless, a cursory scan of some better known early writings yields several instances of water related imagery even in widely different cultural settings, in which the evidence is fairly clear, and which provide some idea on the thinking of early humans.

As early as the eighth century BCE in Greece, the poet Hesiod presented a remarkable description. In a passage with advice to farmers to get dressed warmly and to finish the work in time (Hésiode, 1928; also Hesiod, 1978; vv. 547–553), he wrote the following.

> For the morning is cold when Boreas [the north wind] bears down; in the morning from the starry sky over the earth a fertilizing mist spreads over the cultivations of the fortunate; this [mist], drawn from ever flowing rivers, and lifted high above the earth by a storm wind, sometimes falls as rain toward evening, or sometimes blows as wind, while Thracian Boreas chases the heavy clouds.

This passage contains interesting features; it explains that mist is derived from river water, and that it may lead to rain; on the other hand, it implies that evaporation may be both a result and a cause of the wind. Apart from the reference to Boreas, the god of the north wind, Hesiod's passage appears quite naturalistic.

Several water cycle related passages appear in the Hebrew Bible. The oldest among them, written in the eighth century BCE, is probably (5,8) in the Book of Amos; it reads as follows (see, for example, *Oxford Study Edition*, 1976).

> He . . . who turned darkness into morning and darkened day into night; who summoned the waters of the sea, and poured them over the earth; . . . he who does this, his name is the Lord.

Amos, a native of Judah, was by his own account originally a shepherd and a pruner of sycamore fig trees. From the context, that is from the first part of this quotation which refers to the cycle of day and night, it is possible that the second part refers to some kind of cyclical process as well; but if so, it is a cyclicity in the sense of periodicity and not in the sense of a water cycle. Here also, rain over the Earth results from evaporation from a water surface. A second, more recent, biblical passage of interest is (55,10–11) in the Book of Isaiah, namely, the following.

> This is the very word of the Lord . . . and as the rain and the snow come down from heaven and do not return until they have watered the earth, making it blossom and bear fruit, and give seed for sowing and bread to eat, so shall the word which comes from my mouth prevail; it shall not return to me fruitless without accomplishing my purpose or succeeding in the task I gave it.

Isaiah also lived in the eighth century BCE but this chapter is now generally considered a later addition and attributed to an unknown prophet, who wrote in Babylon toward the end of the exile in the sixth century BCE. In this passage the physical phenomena serve mainly an allegorical purpose and their description is fairly naturalistic; they appear to occur on their own and not as a result of direct divine intervention. The description involves unambiguously some kind of cycle by which water returns to where it came from.

Notions on various cyclical processes were also held in ancient China. In a naturalist work "Chi Ni Tzu," probably of the late fourth century BCE (Needham, 1959, p. 467), atmospheric phenomena are described as follows.

> Wind is the qi [or chhi, spirit, mind] of heaven, and the rain is the qi of earth. Wind blows according to the seasons and rain falls in response to wind. We can say that the qi of the heavens comes down and the qi of the earth goes upwards.

Because the rain is deemed to originate from the Earth even though it falls from above, the direct connection between evaporation and precipitation seems to be taken for granted here.

A passage in the *Chandogya Upanisad* (VI, 10), an important text in Hinduism, which was composed between 800 to 400 BCE, is less explicit; but it is suggestive of the same theme. The passage is an allegory to illustrate the essence of the Self or Being (see Anandatirtha, 1910, p. 458; Radhakrishnan, 1953, p. 460; Swahananda, 1965, p. 458) and can be translated as follows.

> These rivers, my son, flow, the eastern toward the east, the western toward the west. They go from sea to sea. They become the sea itself, and while there, they do not know which river they are.

This text can be interpreted in different ways. The sentence "They go from sea to sea" could conceivably refer to sea currents, or to some underground seawater filtration as the origin of river springs, like that visualized by some in ancient Greece. Still, it is equally plausible that it refers to the evaporation of these waters from the sea and their subsequent precipitation back to the sea. The main point is that it implies a cyclical process.

The above descriptions are merely a few examples. A common feature of most of these early descriptions is that, wherever they imply a water cycling process, they refer to, or hint at, the atmospheric phase of the water cycle. Wherever evaporation is mentioned explicitly it is mostly, though not exclusively, assumed to take place from rivers and the sea. While some of the descriptions include flowing streams, they are silent on the origin of these streams or on whether or how the water returns to where the streams originated. The earliest speculations on this problem, which were not of an obvious mythical nature but based on observations, were probably those of the Greek natural philosophers.

14.2 Greek antiquity

The ancient Greeks are renowned for the large effort their natural philosophers made to arrive at a rational explanation of the world within that same world, without animistic or direct divine intervention. Inspection of their writings and other transmitted evidence indicates that water and various aspects of the water cycle played a central role in their cosmology. As seen in Hesiod's passage, the atmospheric phase of the hydrologic cycle was already a common concept among the Greeks in pre-philosophic times (see also Brutsaert, 1982). Therefore, it is mainly the evolution of their opinions on the origins of springs and rivers, that will be examined in what follows.

14.2.1 The Presocratics

The earliest Greek philosophers who were active in the sixth and fifth centuries BCE are customarily referred to as the Presocratics. Some of their writings were handed down to us in the form of fragments and some were paraphrased by later writers. Among these natural philosophers two competing theories prevailed on the origin of the water in springs, streams, and other fresh water bodies. These are the seawater filtration theory, which was probably the earlier of the two, and the rainfall percolation theory, which contains the essence of our present understanding.

Seawater filtration theory

The basic idea of this theory is that seawater seeps upward through the Earth, loses its salt by filtration and becomes the source of the springs and other surface waters (Figure 14.1). The written evidence points to Hippon as the earliest proponent of this view. Hippon of Rhegion, in what is now southern Italy, also called Hippon of Samos, was a contemporary of Pericles, so he must have flourished around the middle of the fifth century BCE. His opinion on the matter, in the only surviving fragment by him (Diels, 1961, p. 388) is formulated as follows.

> Indeed all drinking waters originate from the sea; for the wells from which we drink are not deeper than the sea. So should the water not be from the sea, then from somewhere else. Now, the sea is deeper than the waters. Thus whatever waters are above the sea, all originate from it.

This fragment is rather terse and not very explicit. However, it should be seen in light of the fact that Hippon's other views were nearly identical with those of Thales, presented at least a century earlier. The following passage by Theophrastos in his *Physical Opinions* (Diels, 1879, p. 475) is revealing.

> Of those who say that the original principle (arche) is one and movable, whom he (Aristotle) calls physicists, some contend that it is bounded; for instance, Thales of Miletos and Hippon, who appears even to (have) become an atheist, said that water is the first principle, being led to this by the observation of the phenomena; for heat thrives in moisture, dead matter dries out, the seeds of everything are moist, and all food is succulent; and naturally each thing is nourished by that from which it originates. Water is the principle of the moisture and the bond of everything. Therefore, they maintained that water is the first principle of everything and that the earth evidently rests on water.

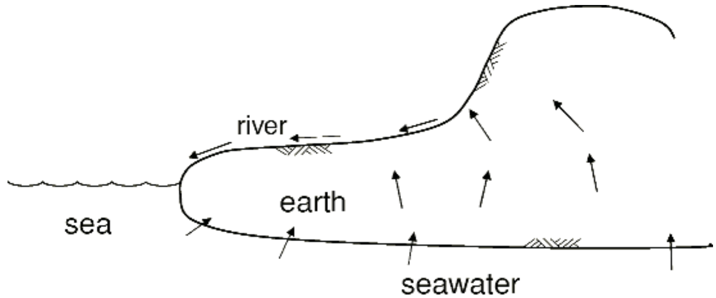

Fig. 14.1 Sketch of the seawater filtration theory of the Presocratic philosophers in ancient Greece. The written evidence points to Hippon as the earliest proponent of this concept, but it was probably Thales with whom it originated.

Thales of Miletos in Ionia flourished around 585 BCE, and he is generally considered to be the first Greek natural philosopher, with whom the formal inquiry started into the reality behind the changes in the Universe. He does not appear to have committed his ideas to writing, and no actual quotations of him have survived. While there is nothing on the origin of rivers or springs, the essence of Thales' views is well known and two of the most important ones are contained in the above passage; these are that the first principle of everything is water, and that the Earth rests on water. Hippon is mentioned here in the same breath as Thales, so it would be surprising if Hippon's opinion on the origin of rivers were very different from that of the old master. It is, therefore, difficult to disagree with Gilbert's (1907) opinion that Thales can reasonably be considered, as the actual originator of the seawater filtration theory, at least among the Greeks. But the roots of this theory may actually be much older. It is now known (see Eliade, 1978) that as early as the third millennium BCE, that is some 2000 years before Thales, in Sumer in lower Mesopotamia it was already a well established view that the Earth rests on the ocean.

Hippon's fragment does not mention the removal of the salt. But this aspect of the theory can be deduced from Aristotle's (1952, II 354 b,15) description, in his objections to this theory, some 200 years later.

> It was this difficulty which led people to suppose that the sea was the primary source of moisture and of all water. So some say that rivers not only flow into it but out of it, and that the salt water becomes drinkable by being filtered.

This is a clear indication that the theory was around at the time of Aristotle and that it was taken seriously by many of his contemporaries.

Rainfall percolation theory

The earliest seeds of this second theory appear in the philosophical views of Anaximander of Miletos; Anaximander, a younger associate of Thales, was born around 610 BCE, and must have been in his prime around 565 BCE. While the issue of the origin of streams and rivers is not addressed directly, his main views can be deduced from the remaining evidence (see also Gilbert, 1907, p. 405). On the nature and the origin of the sea, Alexander of Aphrodisias, a well-known commentator, who flourished around 200 CE, summarized Anaximander's views as follows (Diels, 1879, p. 494).

> Some of them (natural philosophers) say that the sea is the leftover of the original moisture. As the region around the earth was wet, the first of that moisture was evaporated by the sun and became the winds, and from it the turnings of the sun and of the moon as well; thus, as the turnings are caused by the same vapors and by their exhalations, it becomes then the provider of the same (moisture) for those revolving around them. The part of it (the moisture) that is left behind in the hollow places is the sea; therefore, it decreases, as it is continually evaporated by the sun, and eventually it will perhaps have to be dry. Anaximander and Diogenes (of Apollonia) arrived at this view, thus reports Theophrastos.

Anaximander's opinion on what happens to this continual evaporation was summarized by Hippolytus, a Christian writer of the early third century, who died in 235 CE; in his *Refutation* (see Mansfeld, 1992), Hippolytus described it as follows (Diels, 1879, p. 560, 6, 7; 1961, p. 84, 6, 7).

> Winds are generated when the finest vapors of the air are separated off and whenever they are put into motion as they gather; rains are generated from the vapor that is released upward from the earth by the sun.

These two passages indicate that Anaximander considered the sea to be the remainder of the original water around the Earth; the evaporation from the sea is the cause, instead of the result, of the winds and also the cause of the rains. There is no specific mention of streams. Anaximander did not assume, as Thales did, that the Earth floats on water, which would then flow upward to the surface to feed springs and streams; instead, he is known to have posited that the Earth does not rest on anything and that it is suspended in the sky in some sort of equilibrium, because it is equidistant from everything on all sides. Therefore, it is unlikely that he would have assumed that the sea feeds the streams by some upward filtration, as asserted by Thales and Hippon. Rather, it would seem more natural in his scheme that it is a different source of water, perhaps rainwater, which is feeding the streams that flow into the sea. On the other hand, it is clear that he did not think that all the evaporated water ends up in streams and rivers, because the sea is gradually drying out; thus, he definitely did not propose a closed cycle. In any event, he seems to have started, or at least stimulated, a productive line of thought, as can be seen from the views of Xenophanes.

Xenophanes of Colophon (*c*. 570−460 BCE) was probably in his prime *c*. 530 BCE, which is roughly some 35 years after Anaximander. According to Aetius (in Diels, 1879, p. 371, 4; 1961, p. 125, III, 4, 4), a doxographer who probably lived in the first century CE (Mansfeld and Runia, 1997), Xenophanes said that

> . . . what happens in the sky is caused by the heat of the sun; for, when the moisture is drawn out of the sea, the sweet part, which is distinguished by its fine texture, forms a cloud, and drips out as rain by compression like that of felt, and the winds vaporize it around. And he wrote emphatically

(an actual fragment follows in verse, Diels,1961, p. 136)

> The sea is the source of the water, the source of the wind. For in the clouds, neither would the force of the wind, which blows outward, originate without the great sea, nor the flowing of the streams, nor the rainwater from the sky; but the great sea is the generator of the clouds, winds and streams. . . .

Regarding the saltiness of the sea, the opinion of Xenophanes is described by Hippolytus (Diels, 1879, p. 565, 14, 4; 1961, p. 122, 33, 14, 4) as follows.

> The sea is salty, he says, because of the many admixtures which flow together into it.

All this indicates that Xenophanes had some idea of the hydrologic cycle, as we now know it. He not only includes streams in his description, but he specifies that together with the winds, with the rain and with the clouds, the streams are caused by the evaporation from the sea. The only possible interpretation is that this occurs indirectly through the rain on the land surface. This is further supported by his explanation that the saltiness of the sea is

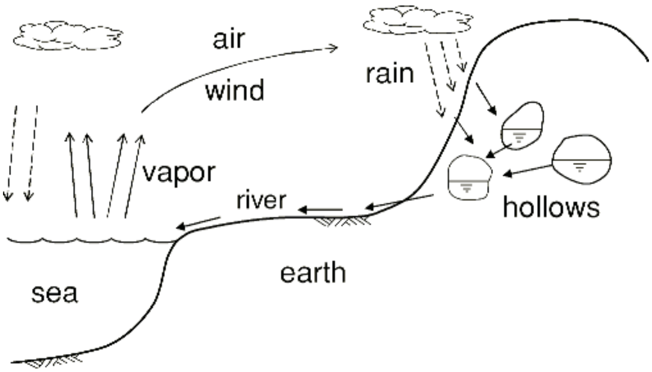

Fig. 14.2 Sketch of the rainfall percolation theory of the Presocratic philosophers in ancient Greece on the origin of rivers. The concept appears to have evolved from rough but seminal ideas by Anaximander, followed by more complete formulations by Xenophanes and Anaxagoras.

caused by the streams which flow into it carrying different salty admixtures picked up along the way. Clearly, the views of Xenophanes are a further development of Anaximander's.

Anaxagoras of Clazomenae (*c*. 500–428 BCE), who came some 70 years after Xenophanes, appears to have been even more explicit on the matter. It is again from Hippolytus (Diels, 1879, p. 562, 8, 4–5) that Anaxagoras is known to have said

> . . . that the sea began to exist from the moist parts on the earth, that it originated this way as the waters in it were being evaporated or settled down, and also from the downflowing rivers; that the rivers take their substance from the rains and out of the waters that are in the earth; for this is hollow and that it has water in the caves.

But the most solid proof that Anaximander, Xenophanes, Anaxagoras and perhaps other Presocratics developed the notion, that the origin of streams and rivers can be accounted for by rain (see Figure 14.2), is found in its attempted refutation by Aristotle in his *Meteorologica*, some one to two centuries later. Evidently, at the time of Aristotle, the rainfall percolation theory was well enough established, that he considered it necessary to mount a head-on attack against it. Aristotle (1952, I 349 b,2) summarized the theory as follows.

> Some people hold similar views about the origin of rivers. They suppose that the water drawn up by the sun when it falls again as rain is collected beneath the earth into a great hollow from which the rivers flow, either all from the same one or each from a different one: no additional water is formed in the process, and the rivers are supplied by the water collected during the winter in these reservoirs. This explains why rivers always run higher in winter than in summer, and why some are perennial, some are not. When the hollow is large and the amount of water collected therefore great enough to last out and not be exhausted before the return of the winter rains, then rivers are perennial and flow continuously: when the reservoirs are smaller, then, because the supply of water is small, rivers dry up before the rainy weather returns to replenish the empty container.

The statement, that "no additional water is formed in the process," is a clear indication that the rainfall percolation theory had eventually led to the concepts of a water cycle and of water mass conservation. From the space devoted to it in Aristotle's *Meteorologica*, the rainfall percolation theory was undoubtedly the more widely accepted at the time.

Both Anaxagoras and Aristotle refer to caves and hollows as the main underground storage spaces of water. This should not be surprising. About 65% of the terrain of Greece is limestone; this is easily eroded, resulting in a karst landscape (Higgins and Higgins,

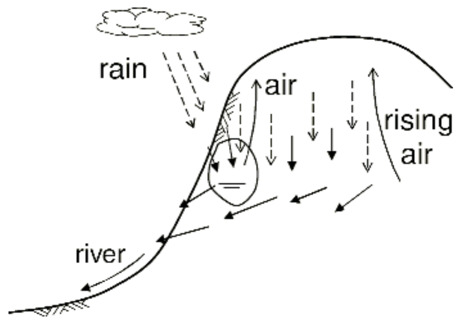

Fig. 14.3 Sketch of Aristotle's theory on the origin of rivers. While rain percolation provides a source of water, this is inadequate to supply the necessary amounts. Another important mechanism, not unlike the generation of rain above the Earth, is the formation of water resulting from cooling and condensation of rising vaporous air inside the Earth.

1996), with sinks, underground streams and caverns. Present day Greece is known to be among the regions of the world most endowed with caves, some seven thousand of them and of all kinds, large and small, vertical, horizontal, inland and along the coast.

14.2.2 Aristotle

It is generally agreed that Greek philosophy culminated with Aristotle (*c*. 384–322 BCE). Even though in antiquity he was acclaimed more as a logician than as a natural philosopher, his influence over the ensuing 18 centuries was to be so large, that it is necessary briefly to review his ideas here.

On the origin of rivers and springs

After having described the Presocratic rainfall percolation theory in the previous quotation, he immediately proceeds to present his own view (Aristotle, 1952, I 349 b,16).

> But it is evident that if anyone tries to compute the volume of water constantly flowing each day and then to visualize a reservoir for it, he will see that to contain the whole yearly flow of water it will have to be as large as the earth in size or at least not so much smaller.
>
> And though it is true that there are many such reservoirs in different parts of the earth, yet it is absurd for anyone not to suppose that the same cause operates to turn air into water below the earth as above it. If then cold condenses vaporous air into water above the earth, the cold beneath the earth must be presumed to produce the same effect. So not only does water form separately within the earth and flow from it, but the process is continuous.

Aristotle does not reject the rainfall percolation mechanism altogether; but he feels that the available underground storage and the amount of rain are inadequate to supply the observed river flows, so that there must be another important mechanism at work. That mechanism is the formation of water out of vaporous air beneath the Earth's surface (see Figure 14.3). Aristotle is correct in that water vapor does condense under the ground in caves; they are often wet and damp and water can be seen to drip from their walls and ceilings. It is now known, however, that the amounts produced this way are very small, and that regular precipitation exceeds by far any kind of condensation beneath the surface as the water supply for springs and streams. Compared to the rainfall theory of the Presocratics, Aristotle's explanation is definitely a step backward in the development of hydrologic theory.

Apparently, however, at this point Aristotle (1952, I 349 b,28) still does not feel that he has presented his argument strongly or clearly enough, because he continues as follows.

> Besides, even if one leaves out of account water so produced and considers only the daily supply of water already existing, this does not act as a source of rivers by segregating into subterranean lakes, as it were, in the way some people maintain: the process is rather like that in which small drops form in the region above the earth, and these again join others, until rain water falls in some quantity; similarly inside the earth quantities of water, quite small at first, collect together and gush out of the earth, as it were, at a single point and form the sources of rivers. A practical proof of this is that when men make irrigation works they collect the water in pipes and channels, as though the higher parts of the earth were sweating it out. So we find that the sources of rivers flow from mountains, and that the largest and most numerous rivers flow from the highest mountains. Similarly the majority of springs are in the neighborhood of mountains and high places, and there are few sources of water in the plains except rivers. For mountains and high places act like a big sponge overhanging the earth and make the water drip through and run together in small quantities in many places. For they receive the great volume of rain water that falls (it makes no difference whether a receptacle of this sort is concave and turned up or convex and turned down: it will contain the same volume whichever it is); and they cool the vapor as it rises and condense it again to water.

Thus the argument is repeated and clarified by contrasting it with yet another theory which, as he explains, holds that rivers originate from preexisting or primal water stored in underground lakes. Reference is undoubtedly made here to the Tartarus theory of his teacher Plato (1975; 1993, 111 d, ff.), which Aristotle discusses and refutes more thoroughly later on (see 355 b,38). The passage is noteworthy in that it indicates that there were others who held this view. But this Tartarus, which also appears in Homer's poetry, is more a throwback to Greek mythology rather than natural philosophy and its discussion is beyond the present scope. Aristotle concludes the paragraph by summarizing once again his own opinion: springs and the sources of rivers result both from rainfall and from condensation inside the Earth.

On why the sea does not overflow

Beside the origin of rivers, Aristotle also concerned himself with the problem why the sea does not overflow, even though all rivers flow into it (Aristotle, 1952, II 355 b,15).

> The place occupied by the sea is, as we say, the proper place of water, which is why all rivers and all the water there is run into it: for water flows to the deepest place, and the sea occupies the deepest place on earth. But one part of it is all quickly drawn up by the sun, while the other for the reasons given is left behind. The old difficulty why so great an amount of water disappears (for the sea becomes no larger even though innumerable rivers of immense size are flowing into it every day) is quite a natural one to ask, but not difficult to answer with a little thought. For the same amount of water does not take the same time to dry up if it is spread out as if it is concentrated in a small space: the difference is so great that in the one case it may remain for a whole day, in the other, if for instance one spills a cup of water over a large table, it will vanish as quick as thought. This is what happens with rivers: they go on flowing in a constricted space until they reach a place of vast area when they spread out and evaporate rapidly and imperceptively.

He calls it an "old difficulty," so it must have been a problem of long standing in Greek philosophy; indeed as seen earlier, Anaximander had already thought about it and had concluded that the sea may eventually dry up altogether. While Aristotle seems to have been the first on record to resolve the issue successfully by providing the correct explanation, it was considered elsewhere as well.

For instance, it appears to have been of concern in ancient China (see Lin, 1949). In the third century BCE during the Zhou (or Chou) dynasty, in the chapter "Autumn Floods", Zhuang Zi (or Chuangtse, d. 275 BCE), raised the issue, as follows.

> There is no body of water beneath the canopy of heaven which is greater than the ocean. All streams pour into it without cease, yet it does not overflow. It is being continually drained off at the Tail-Gate, yet it is never empty. Spring and autumn bring no change; floods and droughts are equally unknown.

According to Lin (1949, p. 120), the editor of the treatise, this tail-gate (Wei-Lou or Wei Lu) is a mythical hole in the bottom or end of the ocean; this depletion mechanism to balance the river inflows is clearly different from the Hippon–Thales seawater filtration mechanism and from Aristotle's evaporation. The same issue was touched upon in the book *Lü Shi Qun Qiu* (or Lu-Shih-Chun-Chiu), written a few decades later during the Qin (or Chin) dynasty by a team of scholars under Prime Minister Lü Bu Wei (or Lu Buwei, d. 235 BCE) (P. K. Wang, 1996; personal communication, 2000), in the following passage (Needham, 1959, p. 467).

> The waters flow eastwards from their sources, resting neither by day nor by night. Down they come inexhaustibly, yet the deeps are never full. The small (streams) become large and the heavy (waters in the sea) become light (and mount to the clouds). This is (part of) the Rotation of the Tao.

The terms within brackets probably represent the interpretation of the text by the translators; but this interpretation is not unreasonable and it would be difficult to come up with a different meaning. Thus here the invoked evaporation mechanism is the same as Aristotle's, and the authors clearly have some kind of hydrologic cycle in mind.

The problem was to continue to receive much attention throughout Western history, and this preoccupation stemmed directly from (1, 7) in Ecclesiastes (*Oxford Study Edition*, 1976) as follows

> All streams run into the sea, yet the sea never overflows; back to the place from which the streams ran they return to run again.

Ecclesiastes dates from the third century, about a century after the death of Aristotle and of Alexander (the Great), when Hellenistic influences had been spreading like wildfire all over the Mediterranean world. The first part of this passage is so reminiscent of Aristotle's, that one has to wonder if the author of Ecclesiastes somehow had not been affected by Greek ideas. Ecclesiastes, like all the other Wisdom books, probably originated in the Jewish diaspora following the Babylonian exile, and possibly even in Alexandria, the very center of Hellenism. To be sure, the book is generally acknowledged to be quite different in literary style from the earlier books of the Hebrew Bible, and it has even been said that some ancient rabbis were distressed by its pessimism. On the other hand, however, the description in the second part is not quite the same as the explanation given by Aristotle. Aristotle unequivocally attributes the fact that the sea does not overflow to evaporation; in Ecclesiastes the way by which "they return" is not specified, but one cannot help inferring some kind of seawater filtration mechanism. At any rate, this passage shows that the "old difficulty" was of concern in Judaism. This preoccupation was also shared later by most Christian writers, and it was to endure well into the Middle Ages. But the theme kept recurring: Dobson (1777) contended that his data supported the wisdom in this biblical passage and, as recently as 1877, Huxley (1900, p. 74) used the passage in his description of the hydrologic cycle.

14.2.3 The Later Peripatetics

Upon Alexander's death in 323, Aristotle decided to leave Athens and he handed over the leadership of the Peripatetic School at the Lyceum to Theophrastos (*c*. 372–287 BCE). From the present vantage point, it would appear that Aristotle's *Meteorologica* continued to be held in high esteem because it was an essential part of the Aristotelian body of works, as it came to the Arab world and later to Western Europe in the thirteenth century. Evidently, however, not all the ideas of the old master were accepted uncritically later on by his successors, and some of them even seem to have been rejected outright. For instance, in the treatise *On Plants*, which is still formally attributed to Aristotle (1936; II 822b, 25) although it is known to be spurious, one reads the following.

Rivers which arise under the ground from mountains behave in the same way. For the matter of which they are composed is rain; and when the water grows large in quantity and is forced into a narrow channel within, the excess of vapor rises from them, which cuts through the earth by pressure from within; and in this way springs and rivers make their appearance.

On Plants became associated with Aristotle's name probably because it was a product of the Lyceum and because it reflected the teaching at the school he had founded. But contrary to Aristotle's explanation in the *Meteorologica*, this passage unambiguously asserts that rivers are composed of rain, and there is no mention of underground condensation. Thus, among later generations at the Peripatetic School, it appears that it was the rainfall percolation theory which gained the upper hand, in spite of its original rejection by Aristotle.

To summarize at this point, Greek antiquity produced essentially four competing theories on the origin of rivers and springs, namely first and foremost, the rainfall percolation theory, which is the one still held today; in addition, there were the seawater filtration theory and the underground condensation theory. Finally, there was also the concept, quite likely based on early popular beliefs and mythology and seemingly less accepted by the philosophers, that rivers originate from underground reservoirs of primal water.

14.3 The Latin era

14.3.1 The Romans

The Romans are mainly praised for their engineering feats and their accomplishments in law and public administration. They are less known for their contributions to natural philosophy and as a result their writings often tend to be dismissed as mere reviews and commentaries on the Greeks. This may be true in general, but it is an oversimplification. With their practical orientation, the Romans usually relied more on observation than on speculation, arriving at interesting insights in some cases. Moreover, for several centuries their writings were the only source of ancient philosophy available in Western Europe; they are therefore an indispensable background to understand and trace the thought currents that brought about the scientific revolution.

The views of Lucretius (*c*. 99–55 BCE) in his work *On Nature* provide a revealing example of some aspects of natural philosophy in Rome. In the following passage Lucretius (1924, V, 261) deals with the problem of why the sea does not overflow and with the origin of springs.

Moreover, there is no need to say how sea, rivers, and springs for ever well up in abundance with fresh waters and their streams flow unceasing: the great pouring down of waters from all sides makes it clear. But, bit by bit, whatever comes first of the water is taken off, and the result is that there is no excess of liquid in the sum total: partly because strong winds sweep the surface and diminish it, as does the sun on high unraveling it with his rays; partly because it is distributed abroad through all the earth underneath; for the pungency is strained off, and the substance of the water seeps back, and all meets at the sources of each river, whence it returns over the earth in a column of sweet water along the path which has once been cut for it in its liquid course.

A more elaborate but similar account is given in VI, 608–638. In contrast to Aristotle's explanation, evaporation is not the only reason why the sea does not overflow; seawater also flows back underground to feed the springs, in accordance with the original theory of Hippon and Thales. Also in contrast to Aristotle, who only considered the sun (Brutsaert, 1982), Lucretius allows for the wind to be involved in the evaporation process. One of Lucretius' aims in writing his book was to promulgate the doctrines of Epikouros, whose natural philosophy, in turn, was derived from the atomic theory of Demokritos and Leukippos; this passage fully reflects this. The main principles of this theory are that nothing can be created out of nothing (or vice versa), which is equivalent with the principle of mass conservation, and that everything is made up of indivisible particles. This explains his view that on the whole there is no excess of water over the original amount, and that the winds are capable of sweeping water particles by evaporation. Unfortunately, beside the works of Lucretius and of Diogenes Laertius (1925) (third century CE), little is left that might give a better idea of what the Greek atomists themselves thought about these hydrologic phenomena.

A completely different example of Roman thought is the comprehensive treatise on architecture by Vitruvius (Marcus V. Pollio), a contemporary of Lucretius in the first century BCE. He composed it after having served as a military engineer under Julius Caesar in Gaul and in Spain. On the generation of spring water he wrote (see Vitruve, 1986, 8, 1) the following.

> We see, in fact, that the rain waters congregate in the hollows found at higher levels in the mountains, where the trees, which grow there in great number, keep the snow for a long time and where, as it melts little by little, it flows out imperceptibly through the veins of the earth; it is this water which, after it reaches the foot of the mountains, produces springs there.

Vitruvius is explicit and specific in attributing springs to rain water and snowmelt which, after infiltrating into the ground, flow out at lower levels. He undoubtedly gained this insight during his military campaigns up north in Gaul, where rainfall and all kinds of seepage outflow phenomena from hillsides are more obvious and more plentiful than in the more arid Mediterranean regions.

Similarly, the writings of Seneca (*c*. 4 BCE−65 CE), born in Cordoba, and teacher and later advisor of Emperor Nero, also give a good idea of the status of natural philosophy among educated Romans. In his work *Natural Questions* he quoted some 40 references, five among them Latin authors, but the remainder Greek. Book Three is devoted to the waters of the earth. He successively discusses five theories on ". . . how the earth supplies the continuous flow of rivers, and where such great quantities of water come from" (Seneca, 1971, III, 4–10.1). Before doing this, he also specifies "Whatever explanation we give of a river, the same will be so of streams and springs." In brief, these five theories are (i) the seawater enters the land by hidden paths (that is why the sea does not increase) and is filtered of its salinity while in transit; (ii) whatever rainfall the Earth receives is sent out again through the rivers; (iii) rivers are supplied by primal fresh water in vast underground reservoirs; (iv) within the deep cavities inside the Earth the stagnant cold air ceases to maintain itself and changes into water; (v) ". . . all elements come from all others: air from water, water from air, fire from air, air from fire . . . so why not water from earth?" Evidently, there are no precedents of this fifth theory, so this must be Seneca's own. The first two are, of course, the theories of the Presocratics, the third apparently a cleaned up version of Plato's Tartarus theory, and the fourth Aristotle's underground condensation theory. While Seneca seems to be willing to admit more than one theory, he is totally opposed to the rainfall percolation mechanism. Because Seneca was to exert such a profound influence on later thinkers, it is important to present his arguments in his own words (Seneca, 1971, III, 7).

> It is obvious that much can be said against this theory. First of all, as a diligent vine-gardener myself I assure you that no rainfall is so heavy it wets the ground to a depth beyond ten feet. All the moisture is absorbed in the outer surface and does not get down to the lower levels. How, then, is rain able to

supply an abundance to rivers since it only dampens the surface soil? The greater part of rain is carried off to sea through river-beds. The amount which the earth absorbs is scanty, and the earth does not retain that. For the ground is either dry and uses up what is poured into it or it is saturated and will pour off any excess that has fallen into it. For this reason rivers do not rise with the first rainfall because the thirsty ground absorbs all the water.

What about the fact that some rivers burst out of rocks and mountains? What will rains contribute to these rivers, rains which pour down over bare rock and have no ground in which to settle? Besides, in very dry localities wells are driven down to a depth beyond a distance of two hundred or three hundred feet and find copious veins of water at a level where rainwater does not penetrate. So you know that no water from the sky exists there nor any collection of moisture, but what is commonly called living water. The theory that all water comes from rain is disproved by another argument: the fact that certain springs well up on the high tops of mountains. It is obvious that they are forced up or are formed on the spot, since all rainwater runs down.

Seneca apparently admits that most rainwater makes its way to river channels, but he feels that this is a short-lived phenomenon and that these quantities are insufficient to maintain a continuous river flow. He bases this argument on observations in his vineyards, which are certainly perceptive, and similar to the findings of Perrault and de LaHire in the late seventeenth century, as will be seen below.

In the later stages of the Roman era Judaic and Christian views gradually gained in influence. In their writings the fathers, or early leaders, of the Christian church displayed a broad knowledge both of biblical accounts and of classical philosophy. But in their eclecticism among the different philosophical concepts they invariably accepted only those that could be reconciled with the biblical narrative. The set of homilies *On the Hexaemeron*, i.e. the six days (of creation), by Basileios of Cappadocia (*c*. 330–379 CE), is an example of this. Basileios had been educated in the classical tradition at Caesarea, Constantinople and Athens, and his writings generally reflect this background. In reference to Genesis (I,1,9) and Ecclesiastes (1, 7), he (Basil, 1963; 4,3) wrote the following.

For this reason, according to the saying of Ecclesiastes 'All the rivers run into the sea, yet the sea doth not overflow.' It is through the divine command that waters flow, and it is due to that first legislation, 'Let the waters be gathered into one place,' that the sea is enclosed within boundaries. Lest the flowing water, spreading beyond the beds which hold it, always passing on and filling up one place after another, should continuously flood all the lands, it was ordered to be gathered into one place.

Then, in (4, 6) he had this to say on the origin of rivers and springs.

In the first place, the water of the sea is the source of all the moisture of the earth. This water passing through unseen minute openings, as is proved by the spongy and cavernous parts of the mainland into which the swift sea flows in narrow channels, is received in the curved and sinuous paths and hurried on by the wind which sets it into motion. Then, it breaks through the surface and is carried outside; and, having eliminated its bitterness by percolation, it becomes drinkable.

Evidently, Basileios judged that among all available theories, the Hippon–Thales view was the main one in harmony with the creation events in Genesis and with the water cycle in Ecclesiastes. Similar views were promulgated some seventeen years later, around 389, by Ambrosius (*c*. 333–397) in his own *Hexameron*, which was partly inspired by that of Basileios. Ambrosius was then Bishop of Milan, but he had been converted to Christianity only at the age of 41, and his early education had been in the classical Latin tradition of the Roman upper class. His descriptions of the origin of rivers (Ambrose, 1961; 3, 2, 10; 3, 5, 22) are nearly the same as those of Basileios. The writings of Basileios and Ambrosius show how the fundamental concept of natural philosophy, as Thales had initiated it, was retained. Thus the Greek tradition of searching for an explanation of the physical world within that same world, without animistic or direct divine intervention, was continued. But the emphasis had shifted somewhat, since this knowledge had to serve as an aid for the transmission of the Christian doctrine and as an illustration of the wisdom of the Creator.

14.3.2 The Early Middle Ages in the Latin West

The *Book on Nature*, written around 613 by Isidorus Hispalensis of Sevilla (*c*. 560–636) for the benefit of Sisebut, king of Visigothic Spain at Toledo, illustrates how this interpretation and approach evolved and were transmitted into the early Middle Ages. Isidore (1960, 41,1) explains why the sea does not grow as follows.

Bishop Clemens says that it is because the naturally salty water consumes the flow of fresh water which it receives, in such a way that, however large the masses of water it receives, this salty element of the sea nevertheless absorbs them totally. Add to this what the winds take away, and what the evaporation and the heat of the sun absorbs. Finally, we see lakes and many ponds being consumed in a short time by the blowing of the wind and the glowing of the sun. And then Solomon says: the streams return to where they come from.

From which it can be understood that the sea does not increase also because, after being returned to their sources through some conduits hidden in the deep, the waters flow back and run back along the usual course through their rivers. But the sea was made purposely so it would receive the runs of all rivers. While its depth is variable, the equality of its surface, however, cannot be discerned. As a result, it is believed that it is called a plain, because its surface is even. But the physicists say that the sea is higher than the land.

The title of Isidore's book is nearly the same as that of Lucretius; also, as noted by Fontaine (in Isidore, 1960) its outline is in many places similar to those of Aristotle, Lucretius, Pliny and Aetius. So to organize his subject matter, Isidore must have had some doxographic references at his disposal, or at least a monastery school manual of such material. But it is striking how in this particular instance, Isidore's treatment on the origin of streams comes closest to the opinion of Lucretius, quoted earlier. (Note that in the past Ecclesiastes has often, evidently mistakenly, been attributed to Solomon). Less than a decade later around 620, Isidore (Isidorus, 1911; 13, 14) again gave a similar account in his book *Etymologies*.

Therefore, the reason why the sea does not increase, although it receives all the streams and all the springs, is as follows: in part, because its own magnitude does not feel the inflowing streams; further, because the salty water consumes the fresh water flows; or because the clouds attract to themselves a large portion of the water; also partly because the winds sweep it up, or partly because the sun dries it up; finally, because after having percolated through some hidden openings of the earth and having been returned to the head of the streams and to the springs, it runs back.

Isidore's writings rapidly spread all over Western Europe, and they had a huge impact. Bede (*c*. 673–735), a Benedictine monk at Jarrow in England, who lived some 100 years later, also wrote a book *On Nature*, which seems to be strongly inspired by Isidore's. His section 40 on why the sea does not increase (Beda, 1843) is an almost literal summary of Isidore's descriptions quoted above. Isidore's influence is also evident in the work of Hrabanus Maurus (*c*. 776–856) of Mainz. Entitled variously *On Nature* or *On the Universe*, it was written around 844, at the height of the Carolingian Renaissance. Intended as an aid for preparing sermons, the text is replete with biblical references and Christian allegories and Hrabanus comes across as a well-read author; however, for his explanation on why the sea does not increase and on the origin of streams and springs, his main source was clearly Isidore. His section on this topic (Rabanus Maurus, 1852; 11, 2) is taken nearly verbatim from Isidore's (13, 14) quoted above.

These few examples show how by the end of the first millennium of the present era a number of concepts of Greek natural philosophy had been propagated in Western Europe through Isidore's writings. If Isidore deserves a place in this history, it is not on account of the originality or correctness – by today's standards – of his cosmological views. However, he was part of a tradition that has some scientific merit. To judge from his specification that the wind is a cause of evaporation, Isidore's hydrologic and meteorologic descriptions were inspired indirectly by those of Lucretius; they are thus related to the views of the earlier atomists Demokritos and Leukippos, rather than those of Aristotle.

14.3.3 The High Middle Ages and the Renaissance

These prevailing concepts in natural philosophy remained roughly the same until the beginning of the thirteenth century, when Aristotle's philosophical works began to draw greater attention in Western Europe. The Latin translations of these works were derived from Greek originals, as a result of intensified contacts with Constantinople during the crusades, and from Arabic translations mostly in Moorish Spain (see Jourdain, 1960; Peters, 1968). In contrast to Western Europe, where his theories had somehow been overlooked until then, possibly as a result of the emphasis on Epicureanism and Stoicism among the Romans, in the Arab world Aristotle had been held in high esteem once his works had become available in translation. This is witnessed by the fact (cf. Mieli, 1966; pp 95, 102) that the famous philosophers Al-Farabi (d. 950) from Turkestan, and the Iranian Ibn-Sina ("Avicenna," 980–1037) have also been called the second and the third master, respectively, after Aristotle. The history of Aristotle's theories in the Arabic world, their subsequent acceptance by the Latins, and their eventual penetration into the vernacular, make for some fascinating reading. In the case of the *Meteorologica*, the first three books were translated early on from a partly abbreviated and corrupted Arabic version by Gerardus Cremonensis (d. 1187), and the fourth book, which does however not deal with meteorologic phenomena, directly from Greek by Henricus Aristippus [d. 1162] (Grabmann, 1916). Roughly a century later, around 1260, a more faithful version of the first three books was produced from the original Greek by Guillelmus de Morbeka (Willem van Moerbeke, *c*. 1215–1286) (Brams and Vanhamel, 1989). As a result, in the course of the thirteenth century, copies of these Latin translations started to appear in Western Europe, and gradually made their influence felt. Also, not long after the Latin translation by Willem, toward the end of the thirteenth century a Norman cleric, Mahieu le Vilain, made a translation of the *Meteorologica* into the French vernacular. An indication of the tremendous influence Aristotle's works must have had, is the fact that for the period between 1200 and 1650 Lohr (1967–1973) lists more than 85 commentaries on the *Meteorologica*, some of them by famous scholars like Alfred of Sareshel (1988), Albertus Magnus, Thomas de Aquino, Johannes Buridanus, Nicholaus Oresme, Themo Judaei de Monasterio (Münster) and others (see also Thorndike, 1954; 1955; Ducos, 1998). Aristotle's influence continued for the next three centuries and at the height of the Renaissance European literature had become fully imbued with many of his physical theories. These theories served not merely as physical explanations, but they were also used as a rich source of metaphors and poetic imagery (Heninger, 1960).

But while Aristotle's ideas were ubiquitous and known by most scholars, they were far from universally accepted. The main effect of Aristotle's *Meteorologica*, like his other works, it seems, was that it generated a common vocabulary, within a coherent system of logic, which stimulated more thorough discussion and the formulation of new questions, but not necessarily the answers, about the nature of the Universe. Thus, contrary to what is usually assumed about medieval scholarship, Aristotle's theories were not always blindly accepted but they often provided the impetus for more correct interpretations. The writings of Buridanus (Jean Buridan, *c*. 1295–1358) from Béthune in Picardy, are a case in point. He is probably best known for his proverbial ass (asinus) and also for the fact that, in rebuttal to Aristotle and some 350 years before Newton, he had some idea of the principle of momentum conservation. In his book *Questions on the three books of Aristotle's Meteorologica* (Ducos, 1998, p. 82), Buridanus wrote the following.

For it is also said to be possible that the water of the sea is evaporated and that the vapor is changed into air, which is carried by the wind to a distant place, and descends there to the earth to replenish the pores to avoid a vacuum, and is there condensed and changed into water, which comes to the spring and then flows to the sea.

In this passage he seems to admit that Aristotle's mechanism of condensation inside the Earth may be possible, but then he continues in direct contradiction of Aristotle, pointing to the rain as the substantial source of the springs.

The waters of springs come from the rains in this manner, because there are in the earth large hollow spaces which receive much rain water in winter, which for some hollow spaces suffices to flow out through the year until the winter rains return, and thus they are perpetual springs, which flow from these hollow spaces. There are other smaller hollow spaces which cannot receive in themselves so much water, which would suffice to flow out through the whole year; therefore, the springs which flow from them dry up in summer.

In other words, if the condensed water could be a substantial source of spring water, springs would not dry up in summer. This shows that among some influential scholars at the University of Paris, rain was taken as the main, if perhaps not the sole, agent in the generation of springs.

Later examples, indicating that the rainfall percolation concept was not uncommon throughout this period, are the accounts by Bernard Palissy (1510–1589) (Palissy, 1888; 1957) and Guillaume de Salluste du Bartas (1544–1590) (du Bartas, 1988, p. 78). Both gave descriptions of the origin of springs and rivers that come generally quite close to the rainfall percolation mechanism as it is known today. It is worth noting that, just like Vitruvius, neither one was famous for his philosophical ideas; Palissy was known mostly for his practical and artistic talents as a ceramist, and Bartas, a soldier and diplomat, for his poetry. Although both were Huguenots, their specific ideas on the origin of springs do not appear to be literal biblical accounts.

But disagreement with Aristotle among some did not necessarily lead to improved concepts among others. For instance, Leonardo Da Vinci (1452–1519), in his notebooks (see MacCurdy, 1938, p. 22) first describes how heat raises water vapor to higher elevations, where it condenses and falls as rain and hail; he then explains how in a similar way the same heat also draws up water from the roots of the mountains, through channels inside these mountains like through the veins inside the human body, to their summits, where the water can flow out through cracks and crevices to create rivers. He also concludes ". . . that the water passes from the rivers to the sea, and from the sea to the rivers, ever making the self-same round . . ." thus implying the seawater filtration mechanism to arrive back at the roots of the mountains. Another example is the description given by Descartes (1596–1650) (1637, p. 179), which was also nearly the same as the seawater filtration theory of old. Hence, the fresh waters which flow into the sea, do not make it any larger because as many others leave it continuously. Some of these waters are raised in the air after being changed into vapors, and then proceed to fall back down as rain or snow on the earth; however, most of these waters penetrate through underground conduits to beneath the mountains; from there the heat, which is in the earth, raises them as vapor to the peaks, where they replenish fountains and rivers. Seawater moving through sand becomes fresh because the salty parts, which are larger, more rigid and interlaced, cannot follow the tortuous paths around the sand grains as easily as the more slippery and smaller fresh water parts, and they are left behind.

14.4 From philosophy to science by experimentation

In the course of the seventeenth century the general approach to science started to change, and gradually experimentation became an essential part of it. Pierre Perrault (1608–1680) and Edme Mariotte (1620–1684) were two central figures at this juncture of the history of hydrology. Their main merit was that, in contrast to the earlier writers on the subject, both relied on experiment and quantitative arguments. But to put their work in proper context, it is necessary to bear in mind the various opinions on the causes and mechanisms of river runoff, as they were then known to them.

14.4.1 The Common Opinion at the end of the seventeenth century

The book *On the Origin of Springs* by Perrault (1674) can provide some insight in this; the first half of it, covering 146 pages, is devoted to a thorough review of the better-known theories and explanations of the day. The authors discussed by Perrault are Plato, Aristotle, Epikouros, Vitruvius, Seneca, Pliny, Thomas de Aquino, Scaliger, Cardano, Agricola, Dobrzenski, Van Helmont, Lydiat, Davity, Descartes, Papin, Gassendi, Du Hamel, Schottus, Rohault, François and Palissy. For each of these authors Perrault first gives a brief description of the main features of the propounded theory, followed by his own critique and reasons for rejection. After completing the survey, he then singles out one of these theories and further specifies (p. 148) how those, who support this particular view,

> . . . believe that the waters of the rains & of the melted snows, which fall on the earth, penetrate it until they encounter heavy (lit. greasy) soil or some other matter, which stops them; whereupon they flow to some opening on the slope of a mountain . . . They believe that the waters, which fall on the high plains, are the cause of the springs, by means of this penetration, which they assume (to take place). . . . They believe that the rains, which fall on the slope of hills, are lost & of no use for the springs, for the reason that from there they fall into the rivers which carry them to the sea . . . They also believe that it is the springs, which being joined together produce rivers, & that if there weren't any springs, there wouldn't be any rivers.

This description of the sequence of processes, which is elaborated on further on pp. 151–152, could have been written today, and it would not be out of place among the descriptions reviewed in Chapter 11. It is remarkable, therefore, that in 1674 Perrault calls this the "Opinion Commune" or "Common Opinion." But even more remarkable is the fact that he also points out that among his 22 "authors," by which he means the learned men and authorities on the subject, only four espoused this opinion, to wit Vitruvius, Gassendi, Palissy and François. In other words, although only a small minority among the expert natural philosophers held this view, he chooses to call it the Common Opinion. Could this mean that toward the end of the seventeenth century, almost everyone else, that is the person "in the street," was already of the opinion that springs and rivers are produced by rainfall percolation?

14.4.2 *The first experimental analyses*

Perrault's interpretations

Not much is known about the life of Pierre Perrault (1608–1680). He was born into a bourgeois family, had at least seven siblings and appears to have spent most of his life in Paris (see Hallays, 1926; Delorme, 1948; A. Picon in Perrault, 1993). Actually, more is known about several of his younger brothers: Claude (1613–1688), one of the original members of the Académie Royale des Sciences, was a physician, a naturalist and an architect; Nicolas (1623–1661) was a doctor in theology, who was expelled from the Sorbonne around 1655 for his Jansenism and known for his denunciation of the Jesuits; Charles (1628–1703) was controller of the King's buildings and author of the Mother Goose fairy tales. Like his father Pierre and his older brother Jean (1610–1669), Pierre Perrault was originally educated for the legal profession. With this background, he purchased the position of Receiver General of Finances for Paris. But because of some unexpected changes in the tax arrangements, around 1664 he came heavily into debt with the royal treasury and was subsequently forced to give up this post. At this point he was essentially broke and turned to hydrology and literature. It is unclear exactly why he set out to focus on the origin of springs. Was it a coincidence that around the same time his brother Claude translated the work of Vitruvius (Vitruve, 1986)? It should be recalled that Book 8 of that work is devoted to this very topic and that Pierre classified Vitruvius (correctly) as one of the proponents of the Common Opinion.

In any event, in the second half of his 1674 book he starts immediately (p. 148) by contrasting his own views with the Common Opinion, as quoted in the previous section, and then (p. 150) he states the two main difficulties with it, as he sees them.

> The first is this supposed penetration of the earth by the waters of the rain, which to me does not seem possible in the manner they mean; the second is that I don't think that enough rain and snow water falls to soak the earth to the extent necessary, nor that there would still be enough left over to make the springs and rivers flow, which are produced by it, as they say, and in the manner they assume.

To support these two objections and to shed some light on the matter, Perrault proceeds to describe a soil water flow experiment he conducted. He took a 65 cm (2 pieds) long lead pipe with a diameter of 4.5 cm (20 lignes), closed off at the bottom with permeable cloth and filled with coarse river sand, and he inserted it about 1 cm (4 lignes) into the water contained in a wide shallow vessel (see Figure 14.4). (The stated dimensions are converted, here and in what follows, by assuming that 1 French inch or 1 pouce = 2.707 cm (Petit Larousse, 1964); also, 1 inch = 12 lines =1/12 foot.) After 24 h he observed that the water had risen and moistened the sand up to a level of 49 cm (18 pouces). To verify whether the risen water could flow out sideways to form springs, he made an opening in the pipe with a diameter of about 1.8 cm (7–8 lignes) at a height of about 5.4 cm (2 pouces) above the water surface, where he attached a small 5.4 cm long gutter, sloping down, in which he placed a strip of paper covered with a thin layer of sand in contact with that of the column. To his surprise, although the paper and the sand in the gutter became moist, never a single drop fell from this little gutter. To check further whether any water would ever flow out, he withdrew the sand column from the water and suspended it for half a day above an empty tray, but again no water flowed out of all that had earlier risen 49 cm. He then poured some water on the top of the column to soak the sand, but only three quarters of it came through at the bottom. The next day, after having poured on again the same amount, all the water passed through. Finally, the following day, he shook all the sand from the bottom of the pipe and observed that the soil which came out first was wet like mortar, whereas that which

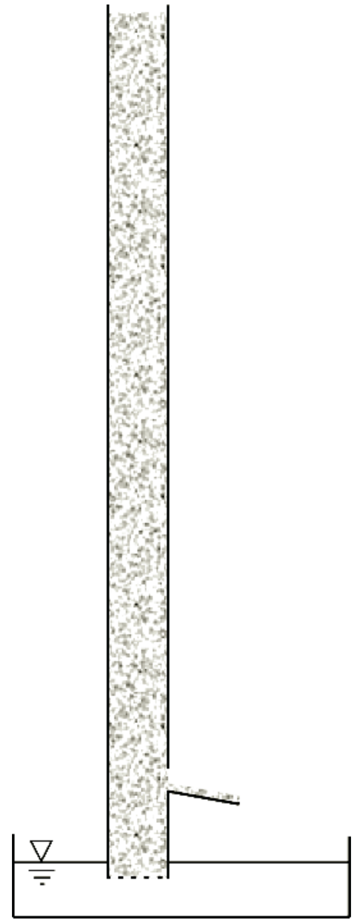

Fig. 14.4 **Reconstruction of the experimental set-up described by Perrault (1674) to measure the movement of water in a sandy soil. The soil was placed in a lead pipe with a length of 65 cm and a diameter of 4.5 cm; the bottom was closed off with permeable cloth. At a height of about 5.4 cm above the water surface an opening was made in the pipe to check whether any water, that had risen into the soil after the bottom had been inserted in the bath, would be able to flow out in the manner of a spring.**

came out last was not so moist, even though he had twice poured water on the sand of the top, which came out last. He repeated the experiment with several other types of soil and set-ups, but the results were similar.

After drawing a number of general conclusions from this experiment, he returns to the two difficulties, which he raised earlier against the Common Opinion (p. 162).

As regards the first one, which is this penetration, which I don't think can take place, as they believe, I will say first, that if we are to believe Seneca and Lydiat. . . . the earth does not allow itself to be penetrated by the rain with such ease as is believed . . . but I add to this reasoning the everyday experiences one encounters with this penetration of the earth.

He further illustrates this inability of water to penetrate by describing the numerous drainage problems encountered by farmers and others dealing with soil water management. Following these general observations in the country side he turns once more to Seneca (p. 166).

The same Seneca asserts that the waters of the rain don't enter into the earth beyond ten feet, which he vouches for as a good wine-grower, which he says he is, who has often dug into the earth.

This shows again the profound influence Seneca's description of his vineyard experience (see Seneca, 1971) continued to have even after 17 centuries. Perrault then recounts how he himself conducted similar experiments and had pits dug in the earth on mountains, on hillslopes, in bottom lands, in cultivated gardens, after long and heavy rains, but he never found the earth moistened beyond a depth of 2 ft. Perrault next invokes the results from his own sand column experiments described above (p. 175).

The second difficulty with this Common Opinion is, that I do not believe that the rains, which fall on the high plains, suffice to maintain the springs, not because of their smallness . . . but because of the waste & the loss of nearly everything which falls on these plains, without any of it benefiting the springs & live fountains . . . For before a certain quantity of water can traverse a certain quantity & thickness of earth, all the particles of this earth must be moistened, each one in particular & with all their surfaces; & this is a pure loss, for this water will only leave by evaporation, because of its adherent property, which causes it to attach itself to everything it touches, and to stay there suspended without moving downward, where its weight should normally attract it, as can be seen by our experiment.

With the Common Opinion disposed of, Perrault turns to the statement of Aristotle, quoted earlier, that the volume of the yearly flows of the rivers is ". . . as large as the earth in size, or at least not so much smaller." Thus he will allow the reader to judge

. . . that these waters of the rivers will not equal the mass of the earth in one year, as he says, but even in a thousand years.

Follows now Perrault's celebrated analysis of the comparison of the flow in the headwaters of the Seine River in Burgundy with the rainfall on the upstream watershed. In brief, he estimated the distance between the source of the river and Ainay le Duc (now Aignay-le-Duc) as roughly 13.5 km (3 lieues) with an average distance to the divides on either side of roughly 4.5 km (1 lieue); with an average annual precipitation estimated at 51.96 cm (19 pouces, 2.333 lignes), this made him conclude that the total annual volume of precipitation over that area was of the order of 224 899 896 muids. (Units of length and volume were not always standardized and they tended to vary in different periods and in different regions; therefore it is not easy to check Perrault's calculations. However, since 1 muid equals 8 ft^3, adopting the conversion that 1 ft is equivalent to 32.484 cm, one finds that this volume is equivalent to roughly 6.167×10^7 m^3; to obtain this volume with the 51.96 cm of precipitation requires the magnitude of the lieue (i.e. the league) in this calculation to be about 4447.7 m. This result is remarkably accurate and shows that Perrault used the "lieue de terre" (land league), which according to the *Petit Larousse* (1964) has a formal length of 4445 m or 1/25 of a degree on a great circle.) He did not have any discharge measurements for the Seine at Ainay le Duc, but by comparing the flow situation to that of the Gobbelins River near Versailles, he guesses it to be about 36 453 600 muids per year, which is roughly equivalent with 1.0×10^7 m^3 per year or 8.42 cm of annual rainfall. This allows Perrault to conclude that

. . . only one sixth of the water which falls as rain and snow on the upstream catchment is needed to make this river run continuously for an entire year . . .

and the remaining five sixths will serve to supply the losses, diminutions and wastes which one observes, as nourishment of vegetation, evaporation and useless outflows. The case of this one river also suggests that rain and snow should suffice for all the other rivers of the world as well, provided one takes the wastes into account.

After thus having shown that the Common Opinion cannot possibly be correct, also that the river flows are not as large as Aristotle had supposed and that the rains are more than adequate to feed the rivers, Perrault (p. 207 ff.) is ready to formulate his views on the origin of springs, the central topic of his treatise. In brief, water cannot penetrate the Earth directly to any appreciable depth. As a result, most of the rain and snow waters, which fall

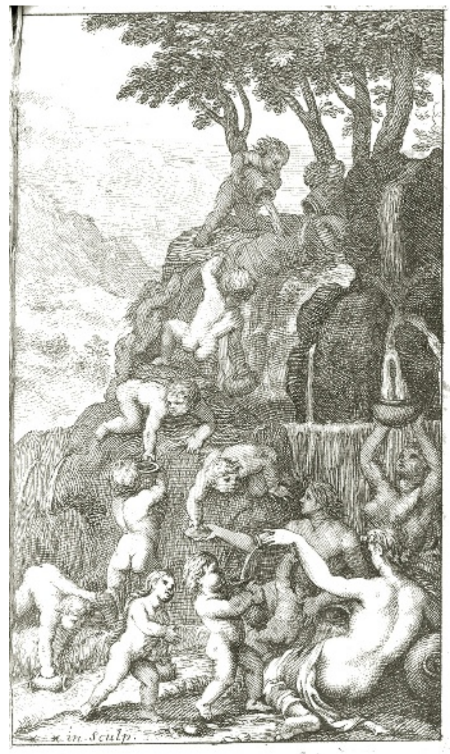

Fig. 14.5 Symbolic representation of the origin of springs in Perrault's (1674) book, showing how nymphs carry water from the river to the mountain top where it can start to flow as a spring. (Courtesy Mandeville Collections Library, University of California, San Diego.)

on the mountains and hills, flow down from the slopes and end up in the rivers and in the creeks; under these rivers and the plains, which they drain, there are layers of clay and other impermeable material; therefore the river waters enter into the more permeable top layers of the plains, mostly laterally, often also by overflowing and flooding. Inside the Earth the water vaporizes by various mechanisms, namely by heat, by cold and by the movement of the air particles, whereupon this vapor rises inside the Earth to the summits of the mountains, where it condenses again to make springs. In support of this explanation, he also invokes the authority of several of the authors of his literature review, among whom Aristotle, Seneca, and Descartes, who had proposed similar mechanisms. His overall conclusion is that, while both springs and rivers are caused by precipitation, in the case of the springs the relationship is indirect, because the water must first enter into the rivers before it can produce springs. Hence springs are not the cause of rivers, but rivers are the cause of springs, so that if there were no rivers there would also be no springs. This imagined transport from rivers to springs was illustrated allegorically in Perrault's book, as reproduced in Figure 14.5.

Considering the state of measurement technology and of open channel hydraulics, Perrault's comparison between river runoff and precipitation was a remarkable feat. So, not surprisingly, in most reviews of the history of hydrology Perrault's work, with its emphasis on experimentation, is rightfully acclaimed as one of the significant landmarks of this science. On the other hand, however, it is usually overlooked, or not fully realized, that in fact one of the main objectives of Perrault's (1674) book, was to refute the largely correct Common Opinion. Thus in this sense, a large part of his work was also a major step backward. Perrault arrived at his erroneous notion mainly on the basis of a sand column experiment and of field observations similar to Seneca's. By today's standards and with present understanding of the underlying physics, his interpretation of these observations was wrong. The reason for this was Perrault's inability to grasp the effects of surface tension on the flow of water in a partly saturated soil. Clearly, the time was not ripe yet and a satisfactory explanation of his column experiment and his field observations would only be possible some 200 years later in the nineteenth century. In any event, whatever damage may have been caused by Perrault's book was soon undone by the more fundamental and perceptive work of Mariotte.

Mariotte's reaffirmation and proof of the Common Opinion

Few facts are known with certainty about the life of Edme Mariotte (Picolet, 1986). He was born around 1620 in Til-Châtel (or Tilchâtel) near Dijon in Burgundy and died in Paris in May 1684; he appears to have spent most of his early life in Burgundy, probably until 1666, when he was elected one of the original members of the newly founded Académie Royale des Sciences (de Condorcet, 1773) and he had to move to Paris. By 1634 he had received tonsure and was therefore a cleric, but there is no evidence that he received higher orders or was ever ordained into the priesthood. Perhaps as early as 1634 he was also appointed prior of St. Martin de Beaumont-sur-Vingeanne, which provided an annual income of some 300 pounds. But this did not involve major responsibilities and his life was essentially devoted to science. While he had many diverse interests (see Davies, 1974), he is now remembered mostly for the law of gases that bears his name, his discovery of the blind spot in the human eye, and his work on the laws of impact between bodies, among many other contributions. A fine example is the constant head device shown in Figure 9.2, which to this day is called a Mariotte flask. As member of the Académie he was also involved in the hydraulic works for the fountains at the king's new castle in Versailles. But it is his major work on this subject, namely *Treatise on the Movement of the Waters and of the Other Fluid Bodies* (Mariotte, 1686), published posthumously, which is of interest here. In the section "On the origin of springs," he first treats the formation of rains, and then unambiguously specifies what happens next (p. 19)

> Having fallen, the rains penetrate the earth through little channels which they find there; thus, when one digs somewhat deeply into the earth, one usually encounters these little channels, whence the water, which gathers at the bottom of what one has excavated, makes the water of wells; but the water of the rains, which fall on the hills & on the mountains, after having penetrated the surface of the earth, mainly where it is light & mixed with pebbles & roots of trees, often encounters clayey soil or continuous rocky formation, which it cannot penetrate and along which it flows to the bottom of the mountain or some considerable distance from the summit, where it comes out again into the open, & forms the springs. This effect of nature is easy to prove, because firstly the water of the rains falls all year long in sufficiently large abundance to maintain the springs & the rivers, as we shall show later on by calculation; secondly, we observe every day that springs increase or decrease according to whether it rains or doesn't rain; & if two months go by without considerable rain, they decrease most of them by one half; & if the drought continues for another two or three months, most of them dry up & the others decrease down to one quarter. From this one may conclude that if there were a whole year without rain, there would be very few springs left, most of which would be very small, or that they would cease altogether.

With his own view clearly explained, Mariotte proceeds in detail to refute some of the mechanisms proposed by others and to provide proof of his own assertions. He first deals with those philosophers who assume that vapors rise from the depths of the Earth to condense into water inside the mountains when they encounter the upper vaults like in an alembic, whence the water flows out to form springs. Mariotte rejects this hypothesis by indicating,

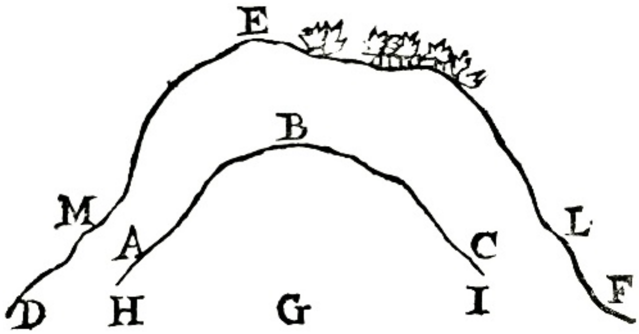

Fig. 14.6 Sketch in support of Mariotte's assertion, that water condensed inside a mountain cannot possibly flow out as a spring. (From Mariotte, 1686; courtesy Division of Rare and Manuscript Collections, Cornell University Library.)

as illustrated in Figure 14.6, that if ABC is a vault in a mountain DEF, the water condensed on this concave surface ABC would fall down to HGI, instead of to L or M, so that it would be incapable of making a spring; he also rejects that there are many such caves. He counters the argument of some that there is earth beside or below ABC, by explaining that in this case the vapors will escape toward A and C, and will yield very little water; moreover, because there is always clayey soil where there are springs, it is unlikely that these condensed waters will be able to pass through from the inside of the mountains.

Next, without mentioning them, he deals with those, like Seneca and Perrault, who claimed that rain cannot penetrate into the soil.

> Still others object that the summer rains, although very big, enter the earth only about half a foot, which one can observe in the gardens & in the tilled fields: I remain in agreement with the experiment. However, I maintain that in non cultivated soils & in the woods there are some little channels, which are quite close to the surface, in which rain water enters, & that these channels extend down to great depths, as one sees in deep dug wells, & that when it rains ten or twelve days in a row, at the end the top of the tilled soils becomes completely wet, & the remainder of the water passes in the little channels, which are below & which have not been broken by tillage.

He goes on to illustrate this with his own observations in the cellars of the Royal Observatory and inside several quarries. In these places water would drip down from the ceiling, but invariably this water could be seen to issue from small holes, crannies and cracks in the rocky vault, while the rest of the surface remained dry; also, this dripping was mostly in response to rain, and would cease during droughts, which suggests that springs are made in the same way. Among many other examples, he notes that during the dry summer of 1681 many wells and springs dried up, and that after a cold spell in the fall they continued to decrease; they would not have done this if the water had been formed by vapors raised from below and condensed by the cold of the surface. Furthermore springs, which are high up in the mountains, are always adjacent to even higher areas, and their flows are larger when these areas are larger; again, this indicates that they are produced by the rains which fall on these higher surfaces.

Finally (p. 30), he addresses the objection by some that the total yearly rain may not be able to supply enough to the great rivers which flow into the sea. He resolves the problem, like Perrault, by comparing river flow with the rainfall on the upstream watershed area; however, his watershed area is much larger and his estimation of the river discharge is also much more rigorous. From measurements over an eight-year period, he estimates the rainfall at Dijon to be about 46 cm (17 pouces), adding that a similar measurement by the "author of the book entitled 'On the Origin of Springs'" yielded a value of 51.96 cm (19 pouces, 2.33 lignes); but for the purpose of the exercise he decides to adopt a conservative value of 40.61 cm (15 pouces). (In his calculations Mariotte assumes that one lieue (league) contains 2300 toises (fathoms); as 1 toise equals 6 pieds, the length of his league is about 4482.8 m, which is slightly different from Perrault's assumed length.) With this value, and assuming that the Seine catchment upstream from Paris occupies roughly 60 286.27 km^2 (3000 square leagues), he figures that this catchment would receive roughly 24.479 km^3 (7.1415×10^{11} ft^3) of rain per year, on average. He estimates the average velocity of the Seine at the Pont Rouge in Paris from float velocity observations of around 1.35 m s^{-1} (250 ft min^{-1}), which he reduces to 0.54 m s^{-1} to account for the effect of bottom and side friction. With a cross-sectional area of the river of 211.04 m^2 (2000 ft^2) this velocity yields an average annual discharge of 3.6032 km^3 (1.0512×10^{11} ft^3); this is equivalent with about 6 cm of water over the whole catchment and is less than 1/6 of the annual rainfall. From this result Mariotte deduces that, even when evaporation, the moistening of surface soils and the replenishment of groundwater are taken into account, there is enough rainwater to produce springs and rivers.

Lest his readers not be convinced and still feel that this result applies only to rivers and not to fountains and springs, as Perrault had argued, Mariotte proceeds next (p. 34) to apply the same analysis to the great spring at Montmartre. He estimates its catchment area as 113 963 m^2 (30 000 square toises) and assumes a rainfall of 48.726 cm (18 pouces), which is equivalent to 55 529 m^3 per year or roughly 0.105 m^3 min^{-1} (107 pintes per minute; there are 35 pintes in a cubic foot). He then explains what happens in the field.

> Now, the terrain of this mountain is sandy to a depth of 0.65 to 1.0 m (2 to 3 feet), & the bottom is clay soil; part of the water of the large rains first runs to the bottom of the mountain, part of the rest stays in the sand near the surface, and the rest flows between the sand and the clay; so, if we assume that it would be only the fourth part of the total, which is . . . 105 l/min (107 pintes per minute), that quarter would be around 26 l/min, which that spring should yield, & that's pretty close to what it yields, when it is running well.

Mariotte's work is without question one of the highlights in the history of hydrology. His treatment is clear and sound enough that it would not be out of place in present-day descriptions, like those reviewed in Chapter 11. His determination of the river discharge rate is based on solid reasoning, and therefore his comparison between precipitation and river flow is a marked improvement over Perrault's calculation a decade earlier. In addition, he shows cogently by different examples that rain water does penetrate the soil in sufficiently large quantities and to sufficiently large depths to be the only possible cause of springs. In this connection, his description of the "little channels or conduits" through which the water penetrates into saturated soil, should establish him as the originator of the concept of macropores. He further supports his ideas on the origin of springs by a mass balance comparison between rainfall and outflow rate from the spring at Montmartre. The reference to Perrault's rainfall measurements shows that Mariotte was familiar with Perrault's book; actually, it would be surprising if he had not been, because he had been working so closely with his brother Claude Perrault at the Académie. This probably also explains why he merely presented his own views, dispassionately, without criticizing or even mentioning Perrault's outlandish theory on the origin of springs.

14.4.3 Lingering doubts and slow acceptance of the Common Opinion . . .

It might be thought that, after the work of Mariotte had put the rainfall percolation theory for rivers and springs on a sufficiently firm foundation, the issue had been settled once and for all. On the other hand, while Mariotte's arguments were sound and indisputable, he had

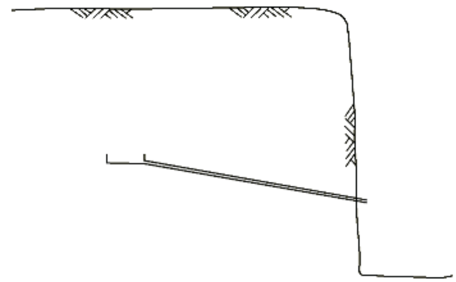

Fig. 14.7 Reconstruction of the experimental set-up described by de La Hire (1703), which was intended to verify the downward movement of water in the soil profile at the lower terrace of the Observatory. A lead basin of 0.422 m^2, with 16 cm high sidewalls, was placed at 2.6 m below the surface; at one of its corners a 3.9 m long pipe was attached to permit outflow of captured water into an adjacent ditch.

only addressed the issue of infiltration in the field, and had totally ignored the puzzling and paradoxical outcome of Perrault's column experiments (Figure 14.4). Because he put the emphasis on the role of macropores, perhaps he felt that the soil column set-up was irrelevant for field conditions.

This apparently did not escape de La Hire (1640–1718), who had in fact been the one to see to it that Mariotte's (1686) book was published posthumously. So, a few years later de La Hire (1703) published the results of another experiment, with a set-up that he specifically designed to check whether precipitation can penetrate the Earth until it would encounter some impermeable layer; he described it as follows (see Figure 14.7).

> I chose a place on the lower terrace of the Observatory, and in 1688 I had a leaden basin with a surface area of 0.422 m^2 (4 feet) installed in the ground at a depth of 2.60 m (8 feet). This basin had sides ("rebords") of 16 cm (6 pouces) height, and it was slightly inclined toward one of its corners, where I had a 3.90 m (12 foot) long leaden tube soldered, which had a considerable slope and which entered in a small excavation at the other end. The basin was kept far from the wall of the excavation, in order that it would be surrounded by a greater quantity of soil similar to that which was on top, and that it would not dry out by the proximity of the wall.

From the present vantage point this set-up, which appears as a forerunner of the lysimeter, had serious shortcomings for its intended purpose; evidently, the basin side walls did not extend to the soil surface, so that percolating rainwater could move away laterally. With present day understanding of the flow in a partly saturated soil, it is no wonder that de La Hire had to report, that "not a single drop of water has come out through the tube in 15 years." He also conducted some experiments with a smaller basin at more shallow depths and under conditions of minimal evaporation, but here some water would only be collected after heavy rainfall and large snowmelt. From these percolation experiments he deduces that rainwater cannot penetrate the earth very deeply. He then proceeded to determine the evaporative loss from two individual fig leaves inserted in water, and this leads him to infer that rain alone is not sufficient to support vegetation in summer, let alone to feed the rivers. In the end de La Hire concludes that the rainfall percolation theory of Mariotte cannot be generally valid; rather, the explanation can only be that there are huge quantities of vapor inside cavities or hollows in the Earth in the form of an alembic, which rise from the waters at the level of the closest rivers or the sea through cracks in the rocks, and that these condense higher up, as a result of the cold at the surface of the Earth, and flow out as springs. Like Seneca's and Perrault's explanations before him, de La Hire's interpretation of his experiments was wide of the mark; indeed a correct explanation of his puzzling seepage phenomena would have to wait for the fundamental work of Laplace (1749–1827) in surface tension and its subsequent application by Buckingham (1907) in soil physics.

The works of Perrault and Mariotte promptly crossed the Channel and were deemed remarkable enough to be reported in the Philosophical Transactions of the Royal Society (Anonymous, 1675; 1686) immediately after their publication. But it is clear that not everybody accepted Mariotte's theory there. Edmond Halley's (1656–1741) reaction is a case in point. Without a doubt Halley was thoroughly familiar with developments in France. In 1681 he had already spent 6 months in Paris where he had become acquainted with several members of the Académie and other learned persons, and had purchased many books of interest to ship back to England (see Cook, 1998); in 1686, at the time of the publication of Mariotte's book, Halley was Clerk of the Royal Society and maintained an extensive international correspondence; he was also editor and publisher of the sixteenth volume of the *Philosophical Transactions*, which contained the review of Mariotte's book. All this makes him almost certainly the author of Anonymous (1686); it must also be his familiarity with this book, no doubt combined with his experiences at sea, which prompted Halley (1687) to engage in the study of evaporation, an aspect of the water cycle, which both Perrault and Mariotte had only dealt with obliquely in qualitative terms. From weight changes during evaporation of water from a small pan he deduces that, on warm days, evaporation amounted to approximately 2.5 mm (0.1 in) in 12 h; this was a reasonable result, as can be seen in Figure 4.16. Halley next uses Mariotte's method to determine the discharge rate of the Thames at Kingston Bridge; the determination of the flow rate this way was far from obvious at the time, as witnessed by the fact that some 15 years earlier Perrault had not quite known how to deal with this same problem. Estimating that the Mediterranean is fed by nine rivers, each of which is ten times larger than the Thames, he concludes that the total inflow into that sea amounts to hardly more than one third of the daily evaporation of 2.5 mm. At a first glance this conclusion is but a confirmation of Aristotle's (correct) explanation of why the sea does not overflow, some 20 centuries earlier. What was new, however, was that now an earnest attempt was made to base Aristotle's speculation on experimental evidence, and not just on everyday observation on a kitchen table. Although his pan evaporation measurements could provide only rough estimates of the actual values for the Mediterranean, Halley's study was probably the first in which evaporation was considered quantitatively in relation to streamflow.

What happens to this evaporated seawater in the global water cycle was the subject of a second paper (Halley, 1691). In brief, all of these vapors are eventually returned to the sea in various ways and this explains why the sea does not decrease even though the evaporation is so much larger than the river inflows. The greater part of these vapors is returned immediately to the sea as rains or dews without ever touching land. Part of the vapors, which are blown off the sea, falls on the lower lands where either it nourishes plants and is exhaled again, or it finds its way into the rivers, after the earth is saturated with moisture, to return to the sea. But most of these vapors are carried by the winds over the low lands to mountain ridges, where part of them precipitates ". . . gleeting down by the crannies of the stone . . .", and part enters the caverns of the hills, inside of which the vapors are collected ". . . as in an alembic, into basins of stone they find there . . ."; this condensed water then breaks out through the hillsides to form springs, which unite further down into rivulets, and eventually into rivers. (Halley's ideas on the origin of springs are also detailed in the *Journal Books of the Royal Society* (MacPike, 1932, pp. 217, 227).) Thus rain is not the only source of all springs. One may wonder why Halley rejected the explanation of Mariotte, whose book most likely had prompted his study in the first place, and why he was misled into invoking, beside rain, direct condensation on the ground and also Aristotle's underground vapor condensation and transport theory for the origin of springs. The explanation appears further down in the text, where he describes the earlier experience that had led him to this condensation theory. In 1677 he had been on an expedition to the Island of St Helena to chart the stars of the Southern Hemisphere; when he was carrying out nighttime celestial observations there on top of a hill some 800 m above sea level, the condensation was so heavy and fast that the droplets on his glasses had to be wiped off every 5–10 min, and the paper on which he recorded his observations became immediately so wet that it would not bear ink.

A more egregious example of reactionary science is Woodward's (1695) explicit reliance on the biblical Abyss or Plato's Tartarus as the ultimate water supply for the springs, rivers, vapors and rains of the earth. Woodward was a Fellow of the Royal Society, and also Professor of Physics at Gresham College in London; he was thus acquainted with Halley. Indeed in 1686 Halley had been elected Clerk of the Royal Society, which held its meetings at Gresham, and it was at that same college that he conducted his pan evaporation experiments (Halley, 1694). The learned men at Gresham College appear to have held various opinions on the origins of springs and rivers, but the Common Opinion was evidently not their favorite one.

Fortunately, the situation was not as dismal everywhere. One influential proponent of the Common Opinion in England was John Ray (1627–1705), naturalist and Cambridge professor until 1662, when he resigned out of religious principle (Raven, 1950). Early on, in fact one year before the publication of Perrault's book, he (Ray, 1673, pp. 296–300) expresses the view ". . . that all springs and running waters owe their rise and continuance to rain, seems to me more than probable . . ."; and he gives as specific reasons that he had never seen running waters breaking out near the top of hills unless there was enough earth above them to feed these springs, that springs generally abate in dry summers, that one seldom finds springs in clay grounds where water sinks in with difficulty, and that those, who would have fountains be fed by the sea, have still not given a satisfactory account of the ascent of water to the mountain tops and its efflux there; with filters and even pumps no such high ascents have ever been produced. He further argues that it is also unlikely that fountains can be attributed to ". . . watery vapors elevated by subterraneous fires, or . . . diffused heat . . . , and condensed by the tops and sides of the mountains as by an Alembick head, and so distilling down and breaking out where they find issue", because the heat required to raise those vapors "through so thick a coat of earth" would be way too large. Finally, he also considers the general statement ". . . that rain sinks not above a foot or two deep into the earth . . ." as manifestly false; as evidence for his assertion he lists the internal flooding of coal mine pits and shafts during wet weather, the near complete absence of surface runoff on sandy and "heathy" grounds even during the heaviest rains, and the fact that the water outflows from caves in the sides of mountains generally increase in the rainy season and often stop completely in dry weather. In a later work Ray (1692; 1693) elaborates on this same theme but in more detail and with additional evidence. For instance, he mentions, without further specifics the "Ingenious French Author", who demonstrated in the Seine that rain may suffice to feed ordinary springs. It is unlikely that Ray had personally read Perrault's book. Rather, as a Fellow of the Royal Society since 1667, he was probably familiar only with the brief review by Anonymous (1675), which contains Perrault's comparison between rainfall and river flow in Burgundy, but nothing on Perrault's theory that springs originate from rivers, a view so at odds with his own. Ray also mentions his own observations on a little brook near his dwelling at Black Notley in Essex, which support his hypothesis that

". . . all its water owes its original to rain." In addition, he specifically addresses Halley's condensation theory. While he admits that Halley's condensation mechanisms may be partly valid in "fervid regions," he feels that they should be of little interest in the production of springs in more temperate countries. The Alps, which are above the fountains of four of the greatest rivers in Europe, are a case in point. Although the Alps are covered heavily with snow for six months of the year, and therefore cannot have any access to vapor, the rivers issuing from them continue to run, albeit low, all winter long without interruption; when the snow melts in spring, some of these Alpine rivers overflow their banks, although no rains fall; but later on after the snow has melted, the streams decay in spite of the vapors that condense on them, and in summer the streams flood again only when it rains; this proves that they are mainly fed by melted snow, as is also indicated by their "sea-green" color.

Ray's writings show that also in England, Halley's and Woodward's views notwithstanding, the Common Opinion was a well-established theory at the time. However, their main importance in the history of ideas stems from the fact that they are among the earliest and more articulate in the renewal of the long tradition, in which use is made of the hydrologic cycle as evidence for God's wisdom in the creation of the world. In this renewed form of the tradition, or "physical theology," which was to last nearly another 150 years, the hydrologic cycle served as a unifying and ordering concept to explain the wisdom behind a number of disparate phenomena on earth, such as mountains, floods and the size of the oceans, which might otherwise have appeared chaotic and paradoxical, in light of, and in contrast to, the obvious perfection of the new Newtonian mechanics. At the time, several others (see, for example, Bentley, 1693, pp. 31–32) were writing on the same theme; but Ray was by far the most popular and widely read author on the subject especially through his book *The Wisdom of God Manifested in the Works of Creation*. This book, first published in 1691, went through twelve editions (Ray, 1759) and continued to be issued until apparently as late as 1827. The underlying idea, namely that the ceaseless circulation of water on Earth is proof of a divine design, became almost a cliché and seems to have exerted a definite imprint on the thinking of intellectuals in England well into the nineteenth century; evidence for this fascination can be found (see Tuan, 1968) in the works of such well known intellectuals as, among others, W. Derham (1657–1735), A. Cooper (3rd Lord Shaftesbury) (1671–1713), J. Hutton (1726–1797), O. Goldsmith (1728–1774), J. Wesley (1703–1791), W. Paley (1743–1805), W. Buckland (1784–1856), J. Kidd (1775–1851), W. Whewell (1794–1866) and even the scientist John Dalton (1766–1844) (1793, p. 145). During the same period similar ideas in physical theology were popular also on the continent with, for instance, such authors as N.-A. Pluche (1688–1761), G. L. L. Buffon (1707–1788) in France, J. A. Fabricius (1668–1736) in Germany (who used the term "Hydrotheology"), and C. Linnaeus (1707–1778) in Sweden.

That the Common Opinion continued to deserve its name is also attested to in the books by the physicist Pieter Van Musschenbroek (1692–1761), the well-known inventor of the *Leyden Jar*, who held successive professorships at the Universities of Duisburg in Westphalia, and Utrecht and Leyden in Holland. In his description of water, Van Musschenbroek (1739, p. 417) asserts the following.

As the rain, the snow, hail and all the vapors fall on the earth, they penetrate it, & flow through the pores, the openings & the cracks, like through underground pipes to the lowest places. If these pipes or conduits are open at the top at one of their ends, fountains are formed thereof, from which the water gushes more or less high, depending on whether the opening in the earth is larger or narrower, or depending on whether the water in the underground conduits presses higher above this opening. But if

> the rain flows out on the surface of the earth into deep hollows, it forms the lakes & the swamps there, from which then rivers are born, which also owe their origin to the waters gushing from the fountains. Consequently, river water is either rain water, or fountain water, or both together.

In a later treatment of the same topic Van Musschenbroek (1769, p. 281) seems to have become aware that this rainfall penetration had presented some difficulties with others in the past. He now addresses the controversy, listing Seneca, Varin, de La Hire, and Buffon, as those who claim that rain cannot penetrate the earth beyond 4–10 ft; he then counters them with his own experience in Holland, as well as with that of Erndetl in Poland, and le Monnier in Auvergne, and repeats essentially his earlier description.

But in spite of the frequent appearance of the hydrologic cycle in physics and in physical theology alike, in none of the treatments reviewed here was there even a hint of calculations, of the kind made earlier by Perrault, Mariotte and Halley; in fact, during the century following their writings the basic notions on the origins of springs and streams did not undergo drastic changes, and many of the disagreements and uncertainties lingered on, it seems. This is brought out in Dalton's (1802a) paper, which he presented in 1799 before the Manchester Literary and Philosophical Society, and which he starts off with the following observation.

> Naturalists, however, are not unanimous in their opinions whether the rain that falls is sufficient to supply the demands of springs and rivers, and to afford the earth besides such a large portion for evaporation as it is well known is raised daily.

This is followed by Dalton's rough estimates for all of England and Wales of average annual precipitation as $P = 787$ mm (31 in), on the basis of measurements at some 23 different sites; of annual dew, as 127 mm (5 in), on the basis of measurements by one Dr. Hales (probably Stephen Hales (1677–1761)); of river runoff, as $R = 330$ mm (13 in), by extending and correcting Halley's estimate for the Thames; and finally of evaporation, as $E = 635$ mm (25 in) per year, on the basis mainly of his own measurements with a simple lysimeter over a 3 y period at Manchester, which combined with the dew amounts to 762 mm annually "raised into the air." Combining these terms in a water budget (cf. Equation (1.1)), in which the dew fluxes cancel out, Dalton ends up with an annual deficit of $(330 + 635 - 787) = 178$ mm (7 in); he attributes this failure to close the budget to a possible underestimate of the average precipitation and, which he feels is more likely, to certain features of his lysimeter, which somehow lost water in heavy storms and which usually kept the soil surface more moist, and therefore must have evaporated more, than the earth around it. He summarizes this part of the paper.

> Upon the whole then I think we may fairly conclude – that the rain and dew of this country are equivalent to the quantity of water carried off by evaporation and by the rivers. And as nature acts upon general laws, we ought to infer, that it must be the case in every other country, till the contrary is proved.

All this is fair enough, but evidently in Dalton's opinion, the closure of the water budget is a separate issue from the origin of springs and not a persuasive argument to prove that precipitation is their sole source. Thus he points out next (p. 367) that at the time

> . . . There are three opinions respecting the origin of springs which it may be proper to notice.
>
> 1st. That they are supplied entirely by rain and dew.
> 2d. That they are principally supplied by large subterranean reservoirs of water.
> 3d. That they derive their water originally from the sea, on the principle of filtration.
>
> It is obvious that before we pay any attention to the latter two opinions, the causes assigned in the first ought to be proved insufficient by direct experiment. M. de la Hire is the only one who has attempted to do this . . .

It is remarkable that, at the dawn of the nineteenth century, these are still essentially the opinions which were being discussed among the Presocratics and Aristotle more than 2300 years earlier. Dalton proceeds then to show that the experimental disproof of the first opinion by de La Hire (1703), was in fact invalid and unwarranted, and this leads him finally to conclude (p. 371) as follows.

The origin of springs may still therefore be attributed to rain, till some more decisive experiments appear to the contrary; and it becomes unnecessary to controvert the other two opinions respecting this subject.

14.5 CLOSING COMMENTS

This previous quotation was probably the last time that any other "opinions" on the origin of springs were brought up in the scientific literature. Still, although the debate on the main issue was closed, details of this "rainfall percolation" continue to be the subject of enquiry to this day, as seen in Chapter 11. In any event, Dalton's (1802a) analysis was a sign that the time was ripe for the rapid developments in the nineteenth century, that laid the foundations for the emergence of hydrologic science in its present form. For instance, it was Dalton (1802b) who introduced next several of the principles on which modern evaporation theory is based (see Brutsaert, 1982, p. 31). He proposed the law of partial pressures in gases and he determined the saturation vapor pressure of water as a function of temperature; he was then the first to express surface evaporation as a mass transfer equation nearly in its current form, and in recognition of this the mass transfer coefficient is still called the Dalton number. Fundamental developments by others followed in rapid succession throughout the nineteenth century, and several of the highlights are mentioned in the previous chapters of this book. But most of this is well-trodden terrain in the history of science, so there is no need to repeat the details.

Among the more striking facts of this historical sketch is that, while humans were able to grasp the essence and the significance of the atmospheric phase of the water cycle very early in prehistoric times, a full understanding of the origin of springs and streams took much longer.

The perceptions and opinions of those who commented on the movement of water in nature, were usually strongly affected by the specific hydrologic conditions in their immediate environment. Some of the early civilizations developed in rather arid and semi-arid climates, where rain, springs and streamflow were not always abundant, so that the linkages of the terrestrial water cycle were not very obvious. A case in point is the eastern Mediterranean region, where karst phenomena are ubiquitous and play a pronounced role. In this perspective many of the early concepts, such as the underground Tartaros or Abyss of Homer and Plato, and the caves of Anaxagoras and Aristotle, can be explained and are not as far-fetched as a superficial review might suggest. Similarly, to Thales or to the writer of Ecclesiastes, who must have known about underground seawater intrusion near the coast or in the Nile delta, the seawater filtration mechanism would not have been unreasonable.

The concept that finally survived, the rainfall percolation mechanism, is not a recent invention. In recorded history it can be followed as a thread running through the works of the pre-Socratics, the post-Aristotelian Peripatetics, Vitruvius in ancient Rome, Buridan and other medieval Schoolmen at the university of Paris, Bartas, Palissy and Gassendi in the Renaissance, and finally Mariotte, Ray and Van Musschenbroek, at the dawn of modern science. But all along it was only one of several competing theories. It is noteworthy that in many instances the rainfall percolation mechanism was advocated by active persons of a more practical inclination, rather than by philosophers. Also, its supporters often tended to have spent their formative years in the countryside in more humid climates with vegetation, and less in denuded arid regions or urban areas, where ubiquitous puddles and overland flow during rain indicate an almost total absence of infiltration. For example, Vitruvius, a rain and snow penetration advocate, had been a military engineer with Caesar's army in Gaul as a young man, before his career in architecture in Rome; during the Renaissance, Palissy was known mostly as a ceramic artist and du Bartas as a soldier and a diplomat. Both Perrault and Halley had grown up in urban environments, while Mariotte and Ray, who were proponents of the Common Opinion, had spent their youth in more rural settings. All this is consistent with the more recent findings on the occurrence of the different flow paths in the streamflow generation processes described in Chapter 11.

REFERENCES

Alfred of Sareshel, *Commentary on the Metheora of Aristotle*, Critical Edition; Introduction, and Notes by J. K. Otte. Leiden: E. J. Brill, 1988.

Ambrose, St, *Hexameron, Paradise, and Cain and Abel*, translated by J. J. Savage. New York: Fathers of the Church, Inc., 1961.

Anandatirtha (Madhvacharya) (1910). *Chandogya Upanisad* (Vol. 3, Part 2 of the Sacred Books of the Hindus). Allahabad: Panini Office, Bhuvaneswari Asrama, Bahadurganj. (Also New York: AMS Press, 1974.)

Anonymous (1675). A particular account given by an anonymous French Author in his book of the Origin of Fountains, printed 1674 at Paris; to shew that the Rain and Snow-waters are sufficient to make Fountains and Rivers run perpetually. *Phil. Trans. R. Soc. Lond.*, **10**, No. 119, 447–450.

Anonymous (1686). (Review of) Traité du mouvement des eaux et des autres corps fluides par feu Mr. Mariotte, A Paris An 1686, Octavo. *Phil. Trans. R. Soc. Lond.*, **16**, No. 181, 119–123.

Aristotle, *Meteorologica*, with an English translation by H. D. P. Lee. London: W. Heinemann, Ltd; Cambridge, MA: Harvard University Press, 1952.

Aristotle, *On Plants*. In *Minor Works*, with an English translation by W. S. Hett. London: W. Heinemann, Ltd; Cambridge, MA: Harvard University Press, pp. 141–233, 1936.

Basil, St., *Exegetic Homilies*, translated by A. C. Way, *The Fathers of the Church*, **46**. Washington, DC: The Catholic University of America Press, 1963.

Beda, Venerabilis, *De Natura Rerum.* In *The Complete Works of Venerable Bede in the Original Latin, Vol. VI*, ed. J. A. Giles. London: Whittaker and Co., 1843.

Bentley, R. (1693). *A Confutation of Atheism From the Origin and Frame of the World, A Sermon Preached at St. Mary-le-Bow, Dec. 5, 1692.* London: H. Mortlock.

Brams, J. and Vanhamel, W. (editors) (1989). *Guillaume de Moerbeke: recueil d'études à l'occasion du 700e anniversaire de sa mort (1286).* Leuven: University Press.

Brutsaert, W. (1982). History of the theories of evaporation. In *Evaporation into the Atmosphere*, chapter 2. Dordrecht: D. Reidel Publ. Co. (Kluwer Academic), pp. 12–36.

Buckingham, E. (1907). *Studies on the movement of soil moisture*. Bureau of Soils, Bull. No. 38. Washington DC: US Department of Agriculture.

Cook, A. (1998). *Edmond Halley, Charting the Heavens and the Seas*. Oxford: Clarendon Press.

Dalton, J. (1793). On evaporation, rain, hail, snow, and dew. Sixth essay in *Meteorological Observations and Essays*. London: W. Richardson. (Also nearly verbatim second edition, 1843.)

(1802a). Experiments and observations to determine whether the quantity of rain and dew is equal to the quantity of water carried off by the rivers and raised by evaporation; with an enquiry into the origin of springs. *Mem. Lit. Phil. Soc. Manchester*, **5** (part 2), 346–372.

(1802b). Experimental essays on the constitution of mixed gases; on the force of steam or vapor from water and other liquids in different temperatures, both in a Torricellian vacuum and in air; on evaporation and on the expansion of gases by heat. *Mem. Lit. Phil. Soc. Manchester*, **5** (part 2), 535–602.

Davies, B. (1974). Edme Mariotte, 1620–1684. *Physics Education*, **9**, 275–278.

de Condorcet, Marquis (1773). *Éloges des académiciens de l'Académie Royale des Sciences morts depuis 1666, jusqu'en 1699*, Hotel de Thou, rue des Poitevins, Paris.

de La Hire, P. (1703). Sur l'eau de pluie, & sur l'origine des fontaines; avec quelques particularités sur la construction des citernes. *Histoire de l'Acad. Roy. des Sciences (Avec les Mémoires de Mathématique & de Physique pour la Même Année), Mém.*, 56–69 (see also Anonym., Sur l'origine des rivières, *Hist.*, 1–6). Paris: J. Boudet. (Republished in 1789 as second edition, pp. 72–90. Amsterdam: P. Mortier.)

Delorme, S. (1948). Pierre Perrault auteur d'un traité *De l'Origine des Fontaines* et d'une théorie de l'expérimentation. *Archives Internationales d'Histoire des Sciences*, **27**, 388–394.

Descartes, R. (1637). *Discours de la méthode, plus la dioptrique, les metéores et la géometrie, qui sont les essais de cette méthode*. Leyde [Leiden]: De l'imprimerie de Ian Maire.

Diels, H. (1879). *Doxographi Graeci*. Berlin: G. Reimer.

(1961). *Die Fragmente der Vorsokratiker*, 10. Auflage herausgegeben von W. Kranz, 1. Band. Berlin: Weidmannsche Verlagsbuchhandlung.

Diogenes Laertius, *Lives of Eminent Philosophers*, Vol. II, with an English translation by R. D. Hicks. London: W. Heinemann; New York: G. P. Putnam's Sons, 1925.

Dobson (1777). Observations on the annual evaporation at Liverpool in Lancashire; and on evaporation considered as a test of the moisture or dryness of the atmosphere. *Phil. Trans. R. Soc. Lond.*, **67**, 244–259.

du Bartas, G. de Salluste, *La sepmaine ou création du monde,* texte préparé par V. Bol. Arles: Édns. Actes Sud, 1988. (First published in 1578.)

Ducos, J. (1998). *La Météorologie en français au moyen âge (XIIIe–XIVe siècles)*. Paris: Honoré Champion Éditeur.

Eliade, M. (1978). *A History of Religious Ideas, Vol. 1. From the Stone Age to the Eleusinian Mysteries* (translated from the French by W. R. Trask, 1962). Chicago: University of Chicago Press.

Gilbert, O. (1907). *Die Meteorologischen Theorien des Griechischen Altertums*. Leipzig: B. G. Teubner.

Grabmann, M. (1916). *Forschungen Über die Lateinischen Aristotelesübersetzungen des 13. Jahrhunderts*, *Beiträge zur Geschichte der Philosophie des Mittelalters*, **18** (5–6). Münster i. W: Aschendorffschen Verlagsbuchhandlung.

Hallays, A. (1926). *Les Perrault*. Paris: Perrin et Cie, Libraires-Éditeurs.

Halley, E. (1687). An estimate of the quantity of vapour raised out of the sea by the warmth of the sun. *Phil. Trans. R. Soc. London*, **16**, No. 189, 366–370.

(1691). An account of the circulation of the watery vapours of the sea, and of the cause of springs. *Phil. Trans. R. Soc. Lond.*, **16**, No. 192, 468–473.

(1694). An account of the evaporation of water, as it was experimented in Gresham Colledge in the year 1693. With some observations thereon. *Phil. Trans. R. Soc. Lond.*, **18**, No. 212, 183–190.

Heninger, S. K. Jr. (1960). *A Handbook of Renaissance Meteorology*. Durham, NC: Duke University Press.

Hesiod, *Works and Days*, ed. M. L. West. Oxford: Clarendon Press, 1978.

Hésiode, *Théogonie; les travaux et les jours; le bouclier*, texte établi et traduit par P. Mazon. Paris: Société d'Édition Les belles Lettres, 1928.

Higgins, M. D. and Higgins, R. (1996). *A Geological Companion to Greece and the Aegean*. Ithaca, NY: Cornell University Press.

Huxley, T. H. (1900). *Physiography*. London: MacMillan and Co. Ltd; New York: D. Appleton and Co. Ltd.

Isidore de Séville, *Traité de la nature (Liber de natura rerum)*, édité par J. Fontaine. Bordeaux: Féret et Fils, Éds., 1960.

Isidorus Hispalensis, E., *Etymologiarum Sive Originum Libri XX ("Etymologiae")*, Tomus II, Oxonii e Typographeo Clarendonio. Oxford: Oxford University Press, 1911.

Jourdain, A. (1960). *Recherches critiques sur l'âge et l'origine des traductions latines d'Aristote* (edition of 1843). New York: Burt Franklin.

Lin, Yutang (editor) (1949). *The Wisdom of China*. London: Michael Joseph Ltd., 1949.

Lohr, C. H. (1967). Medieval Latin Aristotle commentaries. *Traditio*, **23**, 313–413; (1968) **24**, 149–245; (1970) **26**, 135–216; (1971) **27**, 215–351; (1972) **28**, 281–396; (1973) **29**, 93–197.

Lucretius, *De Rerum Natura*, with an English translation by W. H. D. Rouse. London: W. Heinemann, Ltd.; Cambridge, MA: Harvard University Press, 1924.

MacCurdy, E. (1938). *The Notebooks of Leonardo da Vinci, Arranged, Rendered into English and Introduced*, Vol. II. New York: Reynal & Hitchcock.

MacPike, E. F. (editor) (1932). *Correspondence and Papers of Edmond Halley.* Oxford: Clarendon Pess.

Mansfeld, J. (1992). *Heresiography in Context: Hippolytus' Elenchos as a Source for Greek Philosophy.* Leiden: E. J. Brill.

Mansfeld, J. and Runia, D. T. (1997). *Aetiana: The Method and Intellectual Context of a Doxographer.* Leiden: E. J. Brill.

Mariotte, E. (feu) (1686). *Traité du mouvement des eaux et des autres corps fluides* (*mis en lumière par les soins de M. de la Hire, etc.*), Paris: Chez Estienne Michallet.

Mieli, A. (1966). *La science arabe.* Leiden: E. J. Brill.

Needham, J. (1959). *Science and Civilization in China, Vol. 3*, *"Mathematics and the sciences of the heavens and the earth"* (with collaboration of Wang Ling). Cambridge: Cambridge University Press.

Oxford Study Edition, The New English Bible, with Apocrypha. (1976). New York: Oxford University Press.

Palissy, M. B. (1888). *Discours admirables de la nature des eaux et fontaines, etc*. Paris: Martin Le Jeune (1580). (Reprinted in Fillon, B. (1888) *Les oeuvres de Maistre Bernard Palissy*, Vol. 2. Paris: L. Clouzot, Lib.

(1957). *The Admirable Discourses*, translated by A. La Rocque. Urbana: University of Illinois Press. (First published in 1580.)

Perrault, Ch. (1993). *Mémoires de ma vie*, précédé d'un essai d'Antoine Picon: *"Un moderne paradoxal"*. Paris: Macula.

Perrault, P. (anonymously) (1674). *De l'origine des fontaines*. Paris: Pierre Le Petit, Imprimeur & Libraire.

Peters, F. E. (1968). *Aristotle and the Arabs*. New York: New York University Press.

Petit Larousse, *dictionnaire encyclopédique pour tous*. (1964). Paris: Librairie Larousse.

Picolet, G. État des connaissances actuelles sur la biographie de Mariotte et premiers résultats d'une enquête nouvelle. In *Mariotte savant et philosophe (†1684): analyse d'une renommée*, Préface de P. Costabel. Centre A. Koyre. Paris: J. Vrin, pp. 245–276, 1968.

Plato, *Phaedo*, translated by D. Gallop. Oxford: Oxford University Press, 1975.

Plato, *Phaedo* (Greek text), edited by C. J. Rowe. Cambridge: Cambridge University Press, 1993.

Rabanus Maurus, *De Universo [De Rerum Naturis]*. In *Patrologiae Cursus Completus*, Vol. 111. Paris: J.-P. Migne, pp. 10–614, 1852.

Radhakrishnan, S. (1953). *The Principal Upanisads*. London: George Allen & Unwin Ltd.

Raven, C. E. (1950). *John Ray, Naturalist, His Life and Works*. Cambridge: Cambridge University Press.

Ray, J. (1673). *Observations Topographical, Moral, & Physiological*; *Made in a Journey Through Part of the Low-Countries, Germany, Italy, and France: With a Catalogue of Plants* . . . London: J. Martyn Printer to the Royal Society.

(1692). *Miscellaneous Discourses Concerning the Dissolution* and *Changes of the World*. London: S. Smith.

(1693). *Three Physico-Theological Discourses*. London: S. Smith.

(1759). *The Wisdom of God Manifested in the Works of Creation*, twelfth edition. London: J. Rivington.

Seneca, *Naturales Quaestiones*, with an English translation by T. H. Corcoran. London: W. Heinemann, Ltd; Cambridge, MA: Harvard University Press, Vol. I, 1971.

Swahananda, S. (1965). *The Chandogya Upanisad*. Mylapore, Madras: Sri Ramakrishna Math.

Thorndike, L. (1954). Oresme and fourteenth century commentaries on the Meteorologica. *Isis*, **45**, 145–152.

(1955). More questions on the Meteorologica. *Isis*, **46**, 357–360.

Tuan, Y.-F. (1968). *The Hydrologic Cycle and the Wisdom of God: A Theme in Geoteleology*. Toronto: University of Toronto Press.

Van Musschenbroek, P. (1739). *Essai de physique*, traduit du hollandois par Mr. P. Massuet, Tome I. Leyden: S. Luchtmans.

(1769). *Cours de physique expérimentale et mathématique*, traduit par M. S. de la Fond, Tome second. Paris: Bauche.

Vitruve, *Les dix livres d'architecture*, Traduction intégrale de Claude Perrault, 1673, revue et corrigée sur les textes latins et presentée par André Dalmas. Éditions Errance. Paris: A. Balland, 1986.

Wang, P. K. (1996). *Heaven and Earth*. Taipei: Newton Publ. Co., Ltd. (in Chinese).

Woodward, J. (1695). *An Essay Toward a Natural History of the Earth and Terrestrial Bodies, Especially Minerals: As Also of the Seas, Rivers and Springs*. London: Ric. Wilkin.