Part 1

Past theories of rain and snow

To understand what precipitation is, it helps to understand the complete hydrological cycle – evaporation, water vapour, convection, condensation, clouds, soil moisture, groundwater and the origin of rivers. To understand these it is necessary to know what the building blocks of matter are, but three thousand years ago none of this was known. In consequence, up to the fifteenth century there were few sound ideas about how the natural world operated. Most of the suggestions were guesses or were based on superstition, religious dogma, legends or myths. Very few observations were made to help form hypotheses and no predictions made that would help confirm a theory. But these ancient views need to be included in a book dealing comprehensively with precipitation, and the first chapter covers the period from 2000 BC up to the seventeenth century AD. The second chapter traces developments over the 300-year period from 1600 to 1900, during which progress accelerated rapidly.

This whole period is also of interest in that it shows how science and rational thought backed by observation, experiment and measurement were rare in antiquity and are still very new to humanity, having started in earnest only a few hundred years ago. This book might, therefore, also be seen as a demonstration and celebration of the progress of the scientific method and of secular thought.

1

The ancients

Ancient Egypt

Around 2000 BC there were four major civilisations: the Egyptian in the Nile Valley, the Sumerian in Mesopotamia (now Iraq), the Harappans in the Indus valley in India, while in China a civilisation grew up on the banks of the Huanghe (Yellow River). None of these people, as far as we know, measured rain or thought about where it came from.

The Egyptians and Sumerians did, however, undertake considerable hydrologic engineering works between 3200 and 600 BC for water supplies, through the construction of dams and irrigation channels (Fig. 1.1). They also undertook the construction of elaborate underground tunnels (*qanāt* systems) for the transport of water over great distances (Biswas 1970).

The ancient Hebrews

The Hebrews in Palestine collected together old stories told verbally for generations, and from them the Old Testament of the Bible grew. While there are numerous references to rain, there is little to suggest that there was any understanding of its cause. Middleton (1965) remarks that most of the Old Testament references to rain merely stressed how welcome it was, and adds that the Hebrews were satisfied simply to marvel at Nature.

The Greeks

On the other hand, the Greeks, close neighbours of the Hebrews, began around 600 BC to question the processes of the natural world and to pursue knowledge for its own sake, rather than for purely practical purposes. Some of the questions they asked were about water, air, clouds and rain, and we need to look at these to put them in a general historical context.

Figure 1.1 This 'falage' flows though a remote village in northern Oman, fed from a spring in the mountainside. It fulfils all the needs of the villagers from domestic water supply to irrigation of the palms. Such falages have been in use for millennia in the arid regions of the Middle East.

Greek views of the elements

Thales, chief of the 'Seven Wise Men' of ancient Greece, believed that the Earth floated on water and that everything came from water, including earth. The first idea may have come from Homer two centuries earlier (eighth century BC) who thought the Earth was surrounded by a vast expanse of water beyond the sea (*Oceanus*), which had no source or origin. This idea was also common in Egyptian and Babylonian cosmology, in which it was thought that the Earth was created out of the primordial water of *Nūn* and that water was still everywhere below it.

The idea that earth arises from water may have been confirmed with some slight logic when Thales visited Egypt and saw the Nile delta being formed by the river – because of the large amount of volcanic silt carried by the river in its annual flood.

The Nile puzzled the Greeks because its flow peaked in the summer while most rivers reach their maximum discharge during the winter. This puzzle was not finally solved until the Victorian explorers Burton, Speke, the Bakers, Livingstone and Stanley ventured into this difficult country during the nineteenth century, suffering many hardships in the process. But there is no time to explore this interesting digression here.

Speculation about the basic elements that everything is made of continued with Heraclitus, who believed it was fire, while Euripides had the view that the elements were air and earth. Empedocles, however, considered fire, air, water and earth to be the elements from which everything is formed, through combination in different proportions. This view became generally accepted later by Plato and Aristotle.

A contemporary of Thales, Anaximander, believed that all life originated in water and that, through continuous evaporation, land emerged from the all-engulfing sea. He also believed that rain was due to moisture being drawn up from the Earth by the sun and that hail is frozen rain, whereas snow is produced when air is trapped in the water. But he would not have called the process 'evaporation' since the idea of water vapour was still a long way off; nevertheless, this was not a bad summary.

Pythagoras developed the idea that the universe could be explained mathematically. None of his books survives but he later had a key influence on Plato's views about the importance of mathematics, which were incorporated into Plato's teachings at the Academy (see later). His view of the significance of numbers was echoed two thousand years later when Johannes Kepler said 'To measure is to know'. This is also a key assertion of this book.

Xenophanes believed that 'the sea is the source of all water, and the source of wind. For neither could come into being without the great main [sea], nor the stream of rivers, nor the showery water of the sky; but the mighty main is the begetter of clouds and winds and rivers' (Freeman 1948). Observing shells and fossil marine animals on high mountains, he suggested that the land must once have been under the sea – and thereby offered some observational proof of his theory.

The Ionian philosopher Anaxagoras appeared to appreciate that rivers depend for their existence on rain (way before his time), but he also believed that rivers depended on 'waters within the earth, for the earth is hollow and has water within its cavities'. Perhaps this was a way of expressing the idea that water was contained within the soil and rocks as soil moisture and groundwater, which is of course perfectly correct, although this is probably not what he meant.

Hippocrates, the father of medicine, thought that water was made of two parts, one thin, light and clear, the other thick, turbid and dark coloured. The sun lifts the lightest part but leaves behind the salty part. Rain, he believed, was the lightest and clearest of all waters. He actually did an experiment by weighing a container of water, leaving it outside and reweighing it after a day. From the drop in weight

he concluded that the lightest part had been dissipated; the idea of evaporation and of water vapour was implied but not understood in this test. However, the idea of experiments for conducting scientific investigations had been conceived, although unfortunately this was then forgotten for nearly two millennia.

In his play *The Clouds*, Aristophanes mocked the prevailing idea that rain was sent by the almighty god Zeus:

Strepsiades: No Zeus up aloft in the sky!
Then, you first must explain, who it is sends the rain:
Or I really must think you are wrong.
Socrates: Well then, be it known, these send it alone:
I can prove it by arguments strong.
Was there ever a shower seen to fall in an hour
when the sky was all cloudless and blue?
Yet on a fine day, when the clouds are away,
he might send one according to you.
Strepsiades: Well, it must be confessed, that chimes in with the rest:
your words I am forced to believe.
Yet before, I had dreamed that the rain-water streamed
from Zeus and his chamber-pot sieve.

Plato was a pupil of Socrates and was greatly affected by the execution of Socrates in 399 BC on the grounds of invented charges of irreverence and of corrupting the young through his teaching and introducing the ideas of atheism, among much else. Following Socrates's execution, Plato gave up his idea of pursuing politics and instead travelled for 14 years through Egypt, Italy and Sicily studying philosophy, geometry, geology, astronomy and religious matters. On his return to Athens in 387 BC, Plato founded the Academy, an institution devoted to research and teaching in philosophy and the sciences, which he presided over in a passionate search for truth until his death.

Plato accepted the idea that there were four basic elements constituting the universe – fire, air, water and earth, as suggested by Empedocles, who had taken the idea from the theology of the Assyrians (in the northern part of ancient Mesopotamia). Plato's main 'scientific' work is his dialogue *The Timaeus*, and in it he reasons that as the world is solid, God must have placed water and air between the extremes of fire and earth. (See 'The views of Aristotle' below for a more elaborate analysis of these four elements.)

He attempts to put this on a mathematical footing using the 'theory of polyhedra' proposed by the mathematician Theaetetos, which says that there can only be five regular solid figures whose faces are regular, identical polygons. Theaetetos was the subject of two of Plato's *Dialogues*, and Plato assigned four of his polyhedra to the four elements (octahedrons to air, icosahedrons to water, tetrahedrons to fire

and cubes to earth). The fifth, dodecahedrons, were mysterious and Aristotle later said that Plato must have meant heaven!

Plato had two thoughts on the origin of rivers, the first being similar to that of Anaxagoras – the *Homeric Ocean* – in which there are endless large and small passages inside the Earth with a huge subterranean reservoir *Tartarus* filling the Earth, the waters surging to and fro along the passages, either retiring inside or surging back to fill streams and lakes. This view clearly did not involve rainfall in any way and is probably drawn from myths and poets and priests, expanded by Plato's imagination; it was probably not meant to be the literal truth.

But in the second and more realistic proposal, in the dialogue *The Critias*, Plato says that the rainfall (from Zeus, of course) was not lost to the sea but was absorbed by the soil – 'a natural water pot' – acting as a source for springs and rivers. This is one of the first descriptions of the hydrological cycle involving rainfall and appears also to foresee the idea of soil moisture and groundwater and that rivers flow from these.

The views of Aristotle

A student of Plato at the Academy, and subsequently a teacher there, Aristotle left 20 years later when Plato died and took the job of tutor to Prince Alexander (the Great) for seven years until his accession, thereafter returning to Athens, where he set up the Lyceum. His views of 'the universe' are described in the first three books of his *Meteorologica*. Because of the powerful influence of Aristotle at the time and for the next 2000 years, his views are explained here in some detail.

The elements

Like Plato and probably Socrates and many others such as Empedocles, Aristotle believed that there were four 'earthly' elements, *earth*, *water*, *air* and *fire*, and in his *Meteorologica* Aristotle refines these ideas. There seems to have been some mysterious fifth element (perhaps so that he could include all five polyhedra). Each had two qualities from amongst *hot*, *cold*, *dry* or *humid*.

These elements were not seen as separate things but as being convertible one into another; indeed Thales thought they all originally came from water. Conversion was believed to be induced by *rarefaction* and *condensation* and these depend on heat and cold, but they cannot (according to the theory) be changed in any order but only as shown in Fig. 1.2. For example earth cannot change directly into air, but has to change to water first. (Empedocles believed that it was love and hate that brought about the changes – so presumably nothing changed unless there were people about.) In addition each element had a position relative to the others, so that

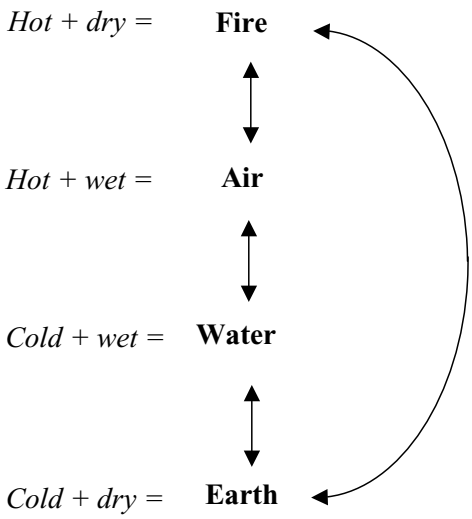

Figure 1.2 Refined by Aristotle, the ancient Greeks believed that everything was composed of four 'elements' – earth, water, air and fire. One could change into another, but only in a certain order, as shown in this diagram. These elements had their own natural positions, fire tending to rise to the top, earth at the bottom, water rising above earth and air above water, but under fire. It was believed that the elements were produced by combinations of *primary qualities* – heat, cold, dryness and moistness, as shown.

fire tended to rise to the top while earth sank to the bottom. Water rose above the earth and air above water, but under fire (Fig. 1.2).

These ideas may sound fanciful now, but one can see how, even through observation if not experiment, this picture of the environment might have been justified. For example clouds can look as if they are appearing 'out of thin air' and a cloud may form over a large fire, the cloud later disappearing, seemingly as if one is changing into the other. They were also aware that the sun evaporated water although they would not have called it that or have understood the process, but it probably made them realise that fire was different to earth, water and air, which are states of matter, whereas fire acts to change the state of the others.

Middleton (1965) explains that the four elements should not be viewed in the same way as our 'elements' of today (hydrogen, helium, lithium . . .), as distinct substances, but rather as 'principles', fire being combustion, not simply a flame, water being fluidity and earth solidity. These ideas were the best that even the cleverest people of the time could come up with, but Aristotle was the first to have made the important step towards something approaching the scientific method, although his failure to make detailed observations or, particularly, to do experiments held back scientific progress until just a few hundred years ago. He believed that all

that was necessary was to think about a problem and to discuss ideas, and that the truth would emerge through logic alone. We had to wait 2000 years for that view to be challenged.

Rain, hail, dew, frost and rivers

In the first three books of *Meteorologica* and in several of his other writings, including *Physics* and *On the Heavens*, Aristotle discusses rain, hail, snow, dew, sea, wind, rivers and springs. In all of this he is bound by the generally prevailing view of the four elements, including the idea that air could be converted to water. Despite this he did not agree with the opinion, held by some, that clouds are simply 'thickened' air, and he seems to have had some insight that clouds were composed of water, for he states that the sun's heat evaporates water at the surface and that this rises. When the heat which caused it to rise is lost, the vapour cools and condenses, turning from 'air' into water. Having become water it then falls again onto the earth as rain. From this it is clear that Aristotle did not appreciate the difference between air and water vapour although he knew that 'vapour' came from the action of heat on water; the concepts of evaporation, condensation and water vapour were still 2000 years away.

Aristotle thought that rain was produced in the clouds, but it is not clear how he thought it occurred. He says:

> The heat in the clouds rises trying to get free from the clouds, while the cold in the vapour opposes the heat driving the two apart. The cold then presses the particles of the cloud together, combining them into drops, and since water naturally moves downwards the rain falls.

He also believed that dew and frost came from moisture that had evaporated in the daytime but had not risen very far.

Aristotle, along with many others, found it a puzzle why hail, being ice, should occur mostly in the summer, for while he (might have) accepted that small cloud droplets could possibly combine to become bigger rain drops, he could not see how small ice particles could join to form hail, so he concluded that the large drops must have formed before freezing. But he could not then explain how these were suspended high in the air. While Anaxagoras correctly thought that hail was formed when a cloud is forced upwards into a cold region, Aristotle simply contradicted this and said that large hailstones were formed near the ground by 'an intense cause of freezing'. He justified this by saying that the cold is 'concentrated within' by the surrounding heat so that in warmer weather it causes the formation of larger raindrops than in winter and sometimes the concentration of cold by the heat is even greater and freezes the drops, making hail. He introduced the analogy of cool caves on a hot day.

The atomists' view of hail, as stated by Epicurus, observing that hail is always associated with a storm, was that it was formed when a small group of 'water atoms' were surrounded by a large mass of 'wind atoms'. Aristotle and many other later writers denied that wind was air in motion, saying that it was 'a dry exhalation from the earth', although Hippocrates and Anaximander believed that wind was moving air.

Aristotle also used the generally accepted belief that the elements were interconvertible to explain the origin of rivers, saying that as air can change into water above the ground, so he assumed it did so underground as well. Living in the dry Mediterranean climate, he believed there was not enough rain to produce the flow of rivers and so proclaimed that what happened was that the mountains acted like sponges and soaked up the air, which was converted into water producing the streams and rivers. The origin of rivers had still not been worked out fully even by the eighteenth century.

Theophrastus succeeded Aristotle as head of the Lyceum, but most of his writings are lost, including those on hydrology, although the latter were translated into Syriac and then into Arabic (in 1446). From these it can be seen that his meteorological concepts were the same as those of Aristotle (Stahl 1962). It also seems as if Theophrastus adopted a meteorological explanation of the origin of rivers and was, therefore, probably the first person to have a reasonable understanding of the full hydrological cycle.

The era of Plato, Socrates and Aristotle represented the golden age of ancient philosophy, when considerable intellectual progress was made. It lasted only about 100 years and over the next few hundred years it faded as Rome took the place of Greece as the centre of civilisation.

The Romans

The ancient Greek civilisation started to decline after 300 BC, and by 100 BC the centre of culture had moved to Rome. The Romans were good practical engineers and built impressive aqueducts and good sewage systems but they did this without any obvious design principles or special solutions for construction; it was all a matter of trial-and-error and experience.

Roman writers had very few independent new ideas and simply collected together all the old beliefs from Greece in immense encyclopaedias. A few did try to establish some basic practical principles but generally the Romans were happy with the status quo. In place of the imaginative exploration of ideas in Greece came the standardising of all knowledge in handbooks, in particular those written by Vitruvius, Seneca, Pliny and Lucretius – enormous compilations of Greek knowledge, mixed in with superstition and travellers' tales. There was nothing new in them,

their saving grace being that they transmitted Greek knowledge, albeit imperfectly, to the early Middle Ages. Without them, much of Greek thought would have been lost, and for this reason alone we need to look at the main players in the Roman arena.

One of the great Roman writers, architects and engineers, Marcus Vitruvius, is known mostly through his books *De architectura*, written around 27–23 BC. Book 8 is devoted to water and like his Greek predecessors Vitruvius believed that 'everything proceeds from water'. Vitruvius had read Aristotle and Theophrastus and so had some rough idea of the hydrological cycle. He noted that valleys between mountains had more rainfall than flat areas and that the snow remained on the ground longer because of the dense forests. He appreciated that as the snow melted it percolated down into the soil and eventually produced stream flow. Like Aristotle and Hippocrates he thought that only the lightest and thinnest and more 'wholesome' parts of water evaporated, leaving behind the heaviest, harsh and unpleasant parts. His descriptions are not precise: for example in explaining why there is always more rainfall near mountains than on plains he says that 'Clouds are supported on a *wave of air* and precipitation occurs when they hit mountains because of the shock sustained and because of their fullness and weight.

His 'bath analogy', however, shows a much better appreciation of the hydrological cycle. In this he says that:

> Hot bath water, being heated, vaporises and rising vapour forms droplets on the ceiling. When the droplets become large enough they fall on the head of the bathers. It is reasonable to assume that since there is no source of water on the ceiling, the water must have come from the bath.

Lucius Annaeous Seneca was a Stoic, best known for his moralistic writing and tragedies. His interest to us lies in his *Natural Questions*, written around AD 63, consisting of seven books dealing with astronomy, physics, physical geography and meteorology. But there is nothing new in them, except that they do differ in saying that the wind is moving air – although he then goes on to say that great amounts of air are emitted from the interior of the earth.

Seneca thought that underground water came from:

(1) The earth contains moisture that is forced to the surface.
(2) Air in the earth is converted to water by 'underground forces of perpetual darkness, everlasting cold and inert density'.
(3) Earth within its interior turns itself into water.

He believed that the earth contained subterranean rivers and massive lakes and a hidden sea which produces all rivers on the surface. In this, he says, 'everyone