Concepts of the hydrological Cycle. Ancient and modern

Les concepts des cycles hydrologiques. Anciens et modernes

James C.I. DOOGE
Centre for Water Resources Research,
University College Dublin, Earlsfarz Terrace Dublin 2 (Ireland)
michael.bruen@ucd.ie

Abstract

The linkage of water and civilisation throughout the ages has resulted in a long history of concepts of the hydrological cycle comprising evaporation, precipitation, percolation and streamflow. For over two thousand years the dominant theory was that, water stored in the sea found it's way into the interior of the earth was lifted by some mechanism or other within the mountains and emerged at a higher level as springs to feed the streamflow returning water to the sea. The modern concept of the cycle, based on the premise that rainfall was more than adequate to account for streamflow, gradually strengthened from the end of the XVIIth Century onwards but was only universally accepted in the XXth century. Many of the key authors involved in this story are better known for other activities and include Plato (427-347 BC), William Caxton (1422-1491), Leonardo da Vinci (1452-1519), Bernard Palissy (1510-1590), Pierre Perrault (1608-1680), Edmond Halley (1656-1742), John Dalton (1766-1844).

Résumé

Le lien entre l'eau et la civilisation à travers les ages a donné naissance à une longue histoire de concepts du cycle hydrologique, comprenant évaporation, précipitation, percolation et écoulement. Pendant plus de deux mille ans, la théorie dominante était la suivante : l'eau contenue dans les mers trouvait son chemin à travers la terre, puis était élevée dans les montagnes par un mécanisme donné et enfin émergeait en altitude sous forme de sources pour alimenter les cours d'eau reconduisant l'eau à la mer. Le concept moderne du cycle, basé sur l'idée que l'eau de pluie était plus que suffisante pour expliquer la présence de cours d'eau, s'est progressivement renforcé à partir de la fin du XVII^{e} siècle mais ne fut universellement accepté qu'au XX^{e} siècle. La plupart des grands auteurs de cette histoire sont plus connus pour d'autres activités, par exemple, Platon (427-347 avant J.C), William Caxton (1422-1491), Leonardo da Vinci (1452-1519), Bernard Palissy (1510-1590), Pierre Perrault (1608-1680), Edmund Halley (1656-1742), John Dalton (1766-1844).

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1. Water in Ancient Cosmologies

The cosmologies of ancient peoples had many features in common and water played a prominent part in all of them. Figure 1 shows the reconstruction of the cosmology of the Book of Genesis by Rabbi Louis Jacobs (Black and Loewe, 1975). It shows among other features the water above the earth (1), the stores of snow (2), hail (3) and rain (4), the heavenly openings (5) and the waters of the deep (9).

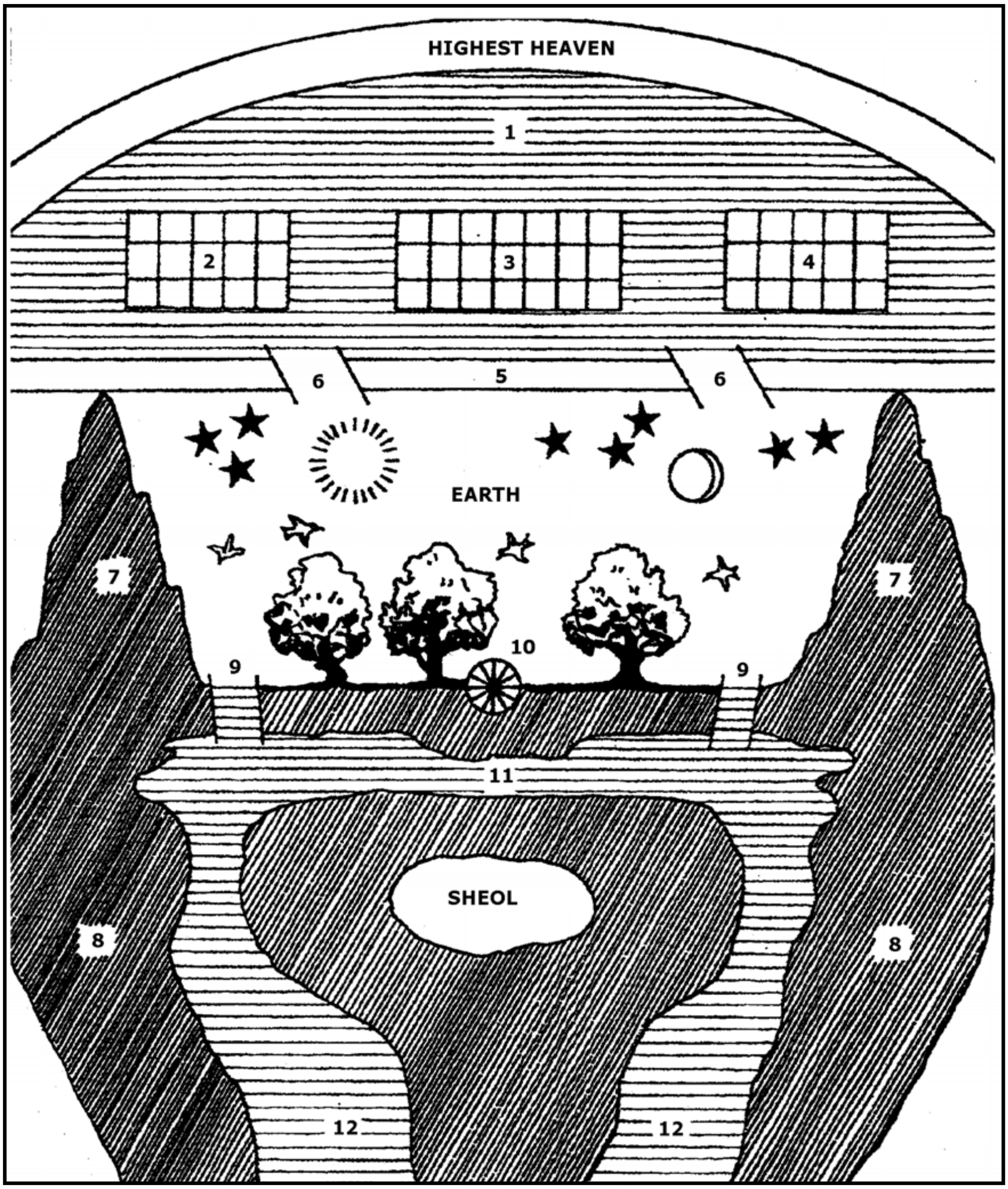

Figure 1: Cosmology of Genesis.

The emergence in the Greek world of primitive concepts of the key hydrologic processes can be traced from both primary and secondary literary sources (Biswas, 1970, pp. 37-71). The widespread concept of the earth floating on a primal ocean is found in Homer (1 000 B.C.). Thales of Miletos (c. 580 B.C.) — referred to by Aristotle as the first of the scientific philosophers — held that "water is the origin of all things". Anaximander (c. 570 B.C.), also of Miletos, described the cause and the movement of water from sea to sky as evaporation, one of the key elements of the hydrological cycle. Xenophobes of Colophon (c. 530 B.C.) added the concepts of water transport by clouds and the production of rainfall from clouds to feed springs and rivers. Anaxagoras of Clazomenaiz (c. 460 B.C.) asserted that the various water processes constituted a closed cycle involving both movement and storage. Diogenes of Appolonia (460-390 B.C.) contended that fresh water evaporated from the sea and later fed the rivers in the form of rain. Plato (c. 390 B.C.) reviewed the work of his predecessors and added the concept of percolation. Aristotle (c. 350 B.C.) wrote of capillary rise within the body of the earth and other topics in some detail in Book I of his Meteorologica (Adams, 1954, pp. 427-431). Thus all the main hydrologic processes were the subject of speculation and comment in the classical Greek world.

Meanwhile similar concepts were being developed in other advanced civilizations. Part of the history of this development in China is discussed by Needham (1959). He quotes Chi Ni Tzu (c. 320 B.C.), who stated:

> *"The wind is the ch'i (matter - energy) of heaven and the rain is the ch'i of the earth. Wind blows according to the seasons and rain falls in response to the wind. We may say that the ch'i of the heavens comes down and the ch'i of earth goes upwards."*

About eighty years later, Lu Shih Ch'un Ch'iu (239 B.C.), wrote:

> *"The clouds go westward and never come to an end, no matter whether it's a summer or a winter. The rivers flow eastwards and never cease to flow regardless of it being night or day."*

and later writes:

> *"The small streams become large and the heavy waters in the seas become light and mount to the clouds. This is part of the Rotation of the Tao (Cycle)"*

The Chinese also considered the earth as floating on a primal ocean.

2. Medieval and Renaissance Concepts

The late development of water science applied to both hydraulics and hydrology, with the initial breakthroughs occurring earlier in hydraulics than in hydrology. The clear establishment of the principle of continuity and of the importance of velocity in water balance by Hero of Alexandria (c. 100 A.D.) was ignored by his contemporaries and by successive generations of water engineers for over 15 centuries. It was formulated clearly but privately by Leonardo (c. 1500 A.D.), and again independently and more thoroughly by Brother Benedetto Castelli whose book on the topic published in 1628 introduced to European audiences this key concept in hydraulics and hydrology.

The concept of the hydrological cycle also suffered from stagnation over the same period. From the time of Plato and Aristotle in the fourth century B.C. to the late Renaissance in the seventeenth century A.D., a basic element in the various concepts of the hydrologic cycle was that the net rainfall (i.e. rainfall minus evaporation) on land was insufficient to supply the total stream flow and consequently some mechanism was required to provide an alternative route to supply springs and streams with water from the sea through a large underground body of water. This general concept is shown graphically on figure 2 due to Garbrecht (1987).

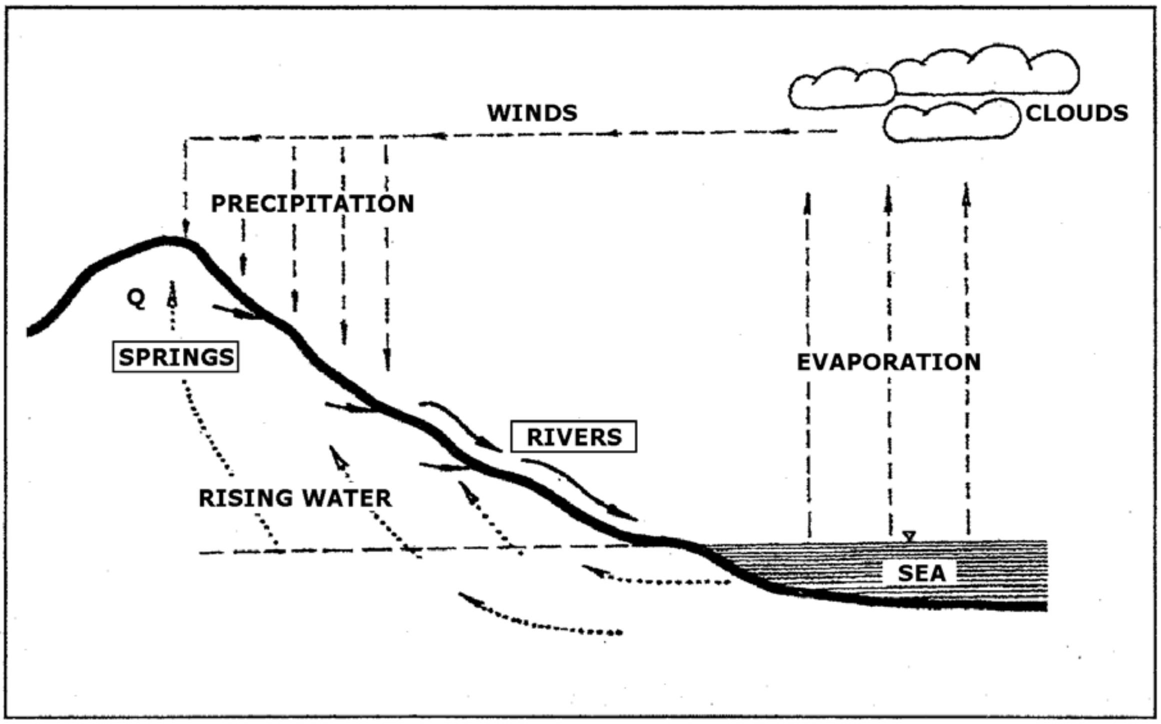

Figure 2: Ancient concept of cycle

Opinions differed on the mechanism responsible for the raising of this water within the earth. Thales (c. 580 B.C.) speculated that the rise might be due to a pressure difference arising from a greater surface elevation in mid-ocean than along the coastline. Plato (c. 390 B.C.) postulated a great underground lake from which the water rose through veins in the rocks and earth. Aristotle (c. 350 B.C.) suggested a mechanism whereby "air" (i.e. water vapour) would rise and then condense at sub-surface levels.

In the high Middle Ages, an alternative explanation for the rising mechanism appears, based on an analogy of living organisms. Thus William Caxton in his Myrror of the World (1481), which was the first encyclopaedia in English, refers to the use of this analogy by Bartholomeus (c. 1240 A.D.) in the words:

> *"Just as the blood of man runs through the veins of the body and issues forth at a particular place, so the water runs through the veins of the earth and to the surface as springs and fountains".*

Around the year 1500, Leonardo da Vinci drew a similar analogy:

> *"Of the raising of the water to the mountains, which acts like water that raises up through plants to the summits, as seen in vines when they are cut; and as the blood works in all animals so water does in the world, which is a living animal".*

Athanatius Kircher, the Jesuit polymath who has been described as "the last Renaissance man", suggested in his 1664 book on Mundus Subterraneus, that the interior heat of the earth as evidenced by hot springs was the source of energy for the lifting process.

The first clear assertion that rainfall over land is sufficient to provide the water in streams and rivers appears to have been that of Bernard Palissy (1510-1590) better known as an innovator in the glazing of pottery. In his Discours Admirables published in 1580, Palissy wrote:

> *"When I had long and closely examined the source of the springs of natural fountains and the places from hence they could come, I finally understood that they could not come from or be produced by anything but rain".*

This percolation concept of the cycle shown on figure 3 (Garbrecht, 1987), for which Palissy advanced several arguments, was not verified experimentally until a hundred years later and not widely accepted for more than a hundred years after that.

3. Early Quantitative Studies

In a book on the "Origin of Fountains" printed at Paris in 1674, a calculation is made to show that "The Rain and Snow-waters are sufficient to make Fountains and Rivers run perpetually". The book in question was the first attempt to apply a quantitative test to a central theme of the debate-whether or not the rain falling on the surface of the ground is sufficient to supply water to all the rivers and springs. (Dooge, 1959, pp. 799-801).

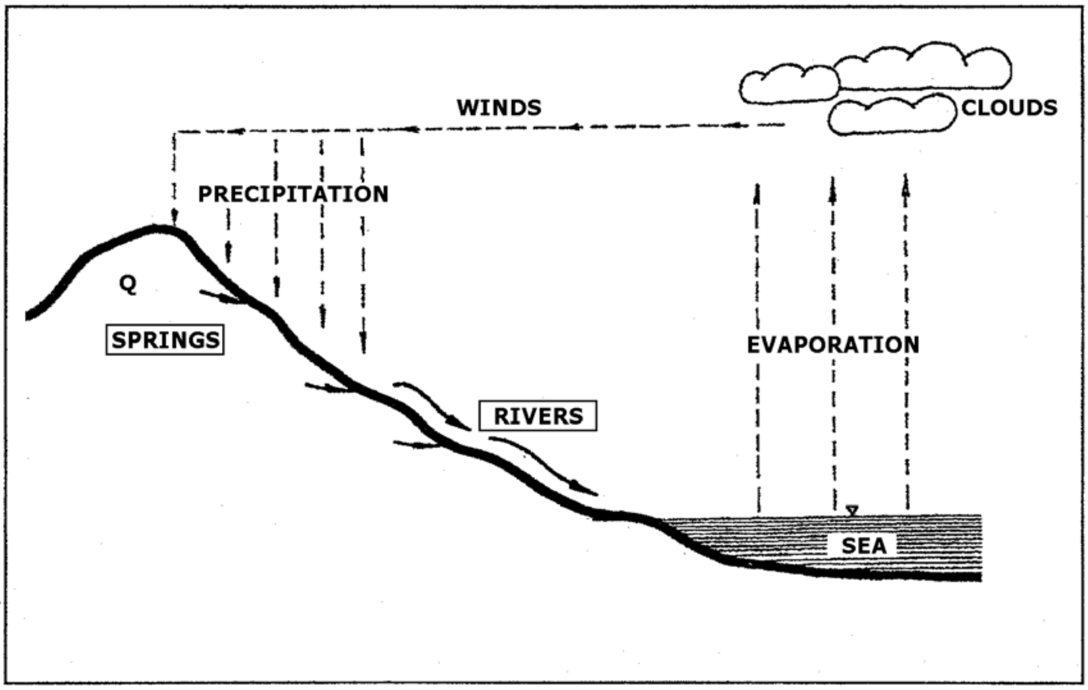

Figure 3: Modern concept of cycle.

The catchment examined was the Upper Seine down to Aignay-le-Duc, where a rivulet enters. The author used the average of three years of rainfall at Dijon as his estimate of precipitation. To estimate the runoff the author compared the flow of the Upper Seine with that of the Gobelins River near Versailles, which had been measured as 50 inches. He estimated the flow of the Seine by comparison as 1,200 inches, "always running, compensating the less quantity it has at its source with the greater it has towards Aignay-le-Duc".

The author's calculations give runoff as one-sixth the rainfall, thus showing that in this case rainfall was more than adequate to supply the river flow. All in all, this first attempt to compare rainfall and runoff was a creditable one for a non-scientist. The author closes his discussion with a comment in which he speaks for all hydrologists when he says:

"I am well aware that this deduction is not sure, but who can give a surer? However such as it is, I think it is more satisfactory than a bare negative as is that of those who pretend it rains not enough to furnish sufficient quantities of water for the constant running of rivers."

This comparison of 1674 is nowadays generally attributed to Pierre Perrault (1608-1680) though there was quite a degree of confusion in regard to the authorship in the literature for two hundred fifty years after its publication (Dooge, 1959, pp. 802-803).

An improved version of the 1674 comparison was included in Mariotte's "Traité du mouvement des eaux et des autres corps fluids" published in 1686, two years after the author's death (Dooge, 1959, pp 801-802). Mariotte (prior of Saint-Martin-sans Beaune near Dijon and an early member of the Academy) based his comparison of rainfall and runoff on the Seine catchment above Paris. Mariotte observed that in flood time a stick carried in mid-stream went as swiftly as a man walking very fast, which he put at one hundred metres per minute. For average flows when the depth is about five feet, Mariotte estimated the surface velocity as sixty metres per minute, and on the basis of double-float experiments took the mean velocity as forty metres per minute. Mariotte also estimated the runoff as less than one-sixth of the estimated rainfall.

As far as the present writer is aware, there was no further advance in the quantitative analysis of the hydrological cycle for another hundred years, except for the 1691 estimate by Halley of the relation between the evaporation from the Mediterranean and the inflow into it (Dooge, 1974, pp. 280-287), and the observations reported by Vallisnieri in 1715 that the direction of the subsurface water in the high Alps was downward not upward. The Journal Book of the Royal Society for February 1691 records: "Halley showed that the hypothesis that all springs are from rains could not well hold". A decade later, Antonio Vallisnieri (1661-1730) who was Rector of Padua University, reached the same conclusion as Perrault and Mariotte that the origin of streams and rivers was to be found in rain and snow melt based on the observations of rivers in the Italian Alps (Adams, 1954, pp. 452-458).

4. The First Complete Water Balance

On March 1st 1799, John Dalton read to the Manchester Literary and Philosophical Society a paper entitled: "Experiments and Observations to determine whether a 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". This paper was afterwards published in 1802, Vol. 5 of the Memoirs of the Society (Dooge, 1974, pp. 289-292). That the work of Perrault, Mariotte and Halley had not determined the nature of the hydrological cycle to the satisfaction of all is evident from the first paragraph of this paper in which the author says:

> *"Naturalists, however, are not unanimous in their opinions whether the rain 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."*

Dalton then proceeds to tackle this problem on the basis of a calculation for an annual water balance for England and Wales. Dalton based his estimate of the average annual rainfall on thirty gauges in England and Wales. He adopted for use in his estimation of the regional water balance the figure of thirty one inches of rain. He constructed a lysimeter ten inches in diameter and three feet deep which was filled with soil and fitted with a drainage pipe at the bottom and a second pipe just below the surface. The mean evaporation found for the three years 1796-1798 was just over twenty five inches. Dalton's estimate of runoff had no such sound observational foundation but was based on an upscaling of an estimate of the flow of the Thames. Dalton by his estimates of rain on the one hand and river discharge and evaporation on the other, obtained a tentative water balance for England and Wales. The computation was found to be out of balance to the amount of seven inches.

That Dalton was concerned with the water balance computation from the point of view of the controversy of the origin of springs is clear from his paper in which he summarized his general conclusion as follows:

> *"Upon the whole then I think that we can finally 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."*

That the evaporation figure of twenty five inches was the cause of discrepancy in his water balance was suggested by Dalton and this is supported in a study by Rodda (1963). Inadequate drainage of Dalton's lysimeter would account for the negative out of balance element.

Though Dalton's computation of the water balance for England and Wales did not result in an exact balance, it was an important contribution to the validation of the percolation concept of the hydrological cycle. The older concept of underground condensation and rising groundwater prevailed among some European experts until well into the XXth century (Meinzer, 1934).

5. Modern Refinements in Measurement

In the XIXth century the principle advances were in the improvements of the measurements of the key elements of the hydrological cycle - rainfall, runoff and evaporation. The details of these developments in relation to rainfall and evaporation are to be found in the references in Chapter W (pp. 861-885) of the excellent Bibliography of Hydrometry by Kolupaila (1961).

In the XIXth century a key development was in the improved measurement of runoff which previously had only been crudely estimated. Woltmann in 1790 had described a vane-type current meter with a revolution counter. However it was only in the latter half of the XIXth century that the use of current meters became popular. In many countries the establishment of systematic hydrometric surveys did not take place until the XXth century. The course of this development can be followed in detail in the monumental Bibliography of Hydrometry compiled by Kolupaila (1961).

The extension of the water balance from catchment and regional scale to global scale took place largely in Russia in the 1870's and 1880's and again in the second half of the XXth century. The other main development in the XXth century was the increase in the physical understanding of the various hydrological processes that form the components of the hydrological cycle. These developments are well presented in the classical texts by Kalinin (1968) on Global Hydrology and by Eagleson (1965) on Dynamic Hydrology. The development of hydrology throughout the XXth century has recently been reviewed by the author (Dooge, 1999).

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